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ASSOCIATE COMMITTEE ON GEOTECHNICAL RESEARCH

PROCEEDINGS OF WORKSHOP ON ICE PROPERTIES

June 21 - 22, 1988
St. John's, Newfoundland

Sponsored by
Centre for Cold Ocean Resources Engineering (C-CORE)
Centre for Frontier Engineering Research (C-FER)
Memorial University of Newfoundland
Faculty of Engineering and Applied Science
National Research Council Canada
Institute for Marine Dynamics
Associate Committee on Geotechnical Research
Snow and Ice Subcommittee
Mobil Oil Canada Ltd.

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JUNE 1989

Canada

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NATIONAL RESEARCH COUNCIL OF CANADA
ASSOCIATE COMMITTEE ON GEOTECHNICAL RESEARCH

PROCEEDINGS OF WORKSHOP ON ICE PROPERTIES

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SPONSORED BY

CENTRE FOR COLD OCEAN RESOURCES ENGINEERING (C-CORE)

CENTRE FOR FRONTIER ENGINEERING RESEARCH (C-FER)

MEMORIAL UNIVERSITY OF NEWFOUNDLAND
FACULTY OF ENGINEERING AND APPLIED SCIENCE

NATIONAL RESEARCH COUNCIL CANADA
INSTITUTE FOR MARINE DYNAMICS
ASSOCIATE COMMITTEE ON GEOTECHNICAL RESEARCH
SNOW AND ICE SUBCOMMITTEE

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Workshop Program

Objective

The objective of the workshop is to evaluate current knowledge concerning ice properties with particular reference to engineering design. It is the intent of the workshop to provide an open forum for discussion.

Chairman: Dr. J-P. Nadreau

Sessions

In each session, there will be a discussion period in which audience participation will be encouraged. A record will be kept of key issues and recommendations arising from the discussions.

1. Ice-structure Interaction In The Field

Chairman: Mr. J.R. Benoit

- nature of the contact between ice and structures: piles, caissons, bridge piers and vessels
- influence of the shape of structures on the type of interaction
- observation of failure modes
- availability of large scale data

Mr. C. Daley	Mr. R.J. Gill
Dr. H. Hamza	Dr. M. Metge

2. Design Requirements

Chairman: Dr. I. Jordaan

- definition of loading scenario
- governing load conditions
- statistical distribution of characteristics of ice features
- statistical distribution of ice properties
- evaluation of critical load conditions

Mr. N. Allyn	Dr. A. Prodanovic

3. Review of Physical Properties of Ice

Chairman: Dr. R. Peters

- ice types
- ice features (ice covers, ridges, icebergs)
- sizes, fluxes, temperature gradients

Dr. J. Lever   Dr. T. Tucker
Dr. S.J. Prinsenberg

4. Review of Mechanical Properties of Ice

Chairman: Dr. L.W. Gold

- identification of mechanical properties required for design
- comparison between various types of ice
- correlation between freshwater, saline and iceberg ice data
- implications of real world load situation

Dr. R. Frederking   Mr. B.L. Parsons
Dr. A.L. Tunik   Dr. O.G. Vinogradov

5. Testing Methods

Chairman: Dr. S. Jones

- methods and techniques used in the lab and in the field
- standardization
- interpretation of results
- control of temperature, rate of loading or of strain, contact between ice and load surface

Mr. J.R. Benoit   Dr. S.N. Chin
Dr. R. Frederking   Dr. R. Gagnon
Dr. J. Molgaard   Dr. J-P. Nadreau

6. Scale effects (physical & analytical)

Chairman: Derek Muggeridge

- dependence of failure mode on scale
- correlation of properties and behaviour between laboratory and field scale
- extrapolation from small to large scale
- case studies

Dr. I. Jordaan   Dr. G.W. Timco

7. Summary Session

Chairman: Dr. J-P. Nadreau

- summary of discussions from the Chairmen
- recommendations

FOREWORD

On behalf of the National Research Council Subcommittee for Snow and Ice, I would like to thank C-CORE for putting on such an excellent workshop on Ice Properties.

Considering industries' recent cutbacks in the Arctic and the layoffs of engineers and scientists working in this field, the large participation in this workshop reflects the excellent planning by C-CORE and the confidence of the participants that this would be a very useful workshop. It also indicates that the field of Arctic engineering is not dead and we will again see Canada a leader in many aspects of this field.

The Snow and Ice Subcommittee is one of four subcommittees of the Associate Committee for Geotechnical Research of the National Research Council of Canada. The other subcommittees are Permafrost, Marine Geotechnical, and Urban Engineering Terrain Problems. Associate Committees were set up to help NRC develop relevant national research policies. The subcommittees were formed to assist the Associate Committee by, firstly, advising on the state-of-the-art on research needs and priorities in the fields, and secondly, promoting communication of research topics within the Canadian technical community.

The Snow and Ice Subcommittee has run many workshops over the years. the last few workshops were:

Mechanical properties of ice in 1977,
Bearing Capacity of Ice in 1978,
Sea Ice Ridging and Pileup in 1980,
Ice Scour in 1981,
Snow Research
Extreme Ice Features in 1986.

The proceedings of all these workshops and other publications by ACGR and its subcommittees are published in NRC Technical Memoranda.

The Subcommittee has 11 members who cover the fields of snow (avalanches, blowing snow) and ice (Beaufort sea, east coast, ice breakers, military, ice mechanics, and ice hydraulics).

The topic of this workshop, ice properties and ice forces on structures is extremely important to the industries operating in ice infested waters. Any over-design of a structure could result in an over expenditure of many tens or hundreds of millions of dollars, any under-design could result in an environmental disaster. It is also very timely, as there have been several fixed structures in the Beaufort Sea which have provided a lot of valuable data. One of these structures is reported to have experienced forces close to its design limit. The workshop covered topics of considerable interest which were presented by very knowledgeable people in the field.

It is very appropriate that this workshop is being held at C-CORE, as this Institute has become a major centre for cold regions research and engineering in Canada.

Finally, I would like to thank Jean-Paul Nadreau and his team for organizing this workshop and C-CORE for hosting the event.

Roger Pilkington
Chairman, Snow and Ice Subcommittee

INTRODUCTION

It was a pleasure for C-CORE to host this Workshop on Ice Properties. St. John's is one of the most appropriate places in Canada to hold such a workshop; the scientific community relates in one way or another to the "ice business" in quite an impressive fashion. St. John's, with its organizations such as Memorial University, C-CORE, the Institute for Marine Dynamics, the Marine Institute and all the oil companies, can be easily labelled as the Centre of Excellence for Ice Studies.

Viewed within the international economic context, the energy issue can sometimes be rather worrying. Canada, however, could be self reliant if the resources available in the Arctic were harnessed. For a little more than twenty years now, Canada has put a large amount of work and energy into the development of its Arctic frontier. Ice is omni-present in this environment and anything which is undertaken has to meet difficult conditions set by the harsh climate. Ice can be a terrible opponent but if well mastered, it can also be the most useful partner. In both cases the only way to control the situation is to know the material well.

Considering the amount of knowledge acquired on ice so far and the number of structures already designed and built to resist it, it would be most interesting to evaluate how the two are related and what is still needed to improve the safety factors and the economic efficiency of offshore structures. The objective of this workshop was to evaluate the current knowledge concerning ice properties with particular reference to engineering design. The intent was to provide the participants with an open forum for discussion.

I think we can say that the workshop was a great success. We foresaw this workshop as a means of giving people from different sectors an opportunity to discuss all issues freely. We expected to attract around 45 participants; 65 people actually attended the workshop. The high calibre presentations, the lively discussions and the warm (and windy!) ambience, typical of Newfoundland, turned this workshop into an instructive and profitable event.

This success would not have been possible without the kind and cheerful participation of the speakers, the chairpersons and of course, the attendees. It would also have been impossible to make it run so smoothly without the help of C-CORE's support staff. I would like to take this opportunity to thank the numerous sponsors who assisted in the organization of the workshop at all levels. Finally, my personal thanks are specifically directed to Dr. Lorne Gold and Ms. Judith Whittick who undertook a large part of the planning of the workshop. I am very grateful to them for their tireless contribution.

Speakers at the workshop were invited to submit extended abstracts of their presentations and respond in writing to questions that had been directed to them during the discussion periods. This Workshop Proceedings is an amalgamation of their responses.

Jean-Paul Nadreau
Workshop Chairman

ICE-STRUCTURE INTERACTION IN THE FIELD

SESSION 1

COMPARISON OF FULL SCALE/MODEL SCALE M.V. ARCTIC ICE INDENTATION

Claude Daley
Fleet Technology Limited

Session 1 Topics

- Nature of Ice Contact
- Influence of Shape
- Observations of Failure Modes
- Availability of Full Scale Data

All of these topics will be addressed in the presentation.

Q. What happened when the M.V. Arctic rammed multiyear ice?

How did the ice respond on an overall basis?

How good is the "model"?

Items to be Covered

1) Field Trials of the M.V. Arctic - Forces, Indentation, P/A

2) Model Tests of the M.V. Arctic - Forces, Problems of Strength Scaling

3) Analysis of Contact by Kaj Riska Failure Number "Lamda", Nominal Pressure

4) Controlled Indentation Tests in Model Ice
Why is Pressure Constant?
Why P_{nom} a lower bound?

5) Sources of Error in Full-Scale Analysis

6) Nature of Contact
- Model, Theory, Full Scale

The captions and explanations of the figures used during this presentation are given on pages 4 to 6. The figures themselves are on pages 7 to 19.

(1) This is full scale data from the 1984 ramming trials of the MV ARCTIC. Vertical force is plotted versus indentation for rams into heavy multi-year ice. A curve fit has resulted in:

$$F = cI^{.98}$$

The validity of this equation will be discussed.

(2) This plot is from a report on physical model tests which attempted to replicate the full scale trials of the MV ARCTIC. The first plot is of indentation (here referred to as V_{GR}) versus ice strength. While normal dynamic scaling would have resulted in a uniaxial strength of approximately 125 kPa (scale factor was 40), the required strength to achieve the correct indentation was approximately 20 kPa. This apparent anomaly was found for all types of model ice used (Arctec's MOD-ICE, foam-concrete and Wartsila's FG-ICE).

(3) These figures come from Kaj Riska's doctoral thesis (Technical University of Helsinki, 1987). Dr. Riska developed the concept of an ice failure number λ, for an indentation of a certain shape. λ is a function of the 3-dimensional failure surface and the geometry of contact. Using an average value of λ over the contact area, a nominal failure pressure P_{nom} can be defined.

(4) Values of P_{nom} were determined for both the full scale trials condition, and an ice block edge crushing experiment (performed in the lab). It was found that the calculated values of P_{nom} were in good agreement with the small area contact pressures found in the experiments. This suggested a starting point for a pressure/area curve.

(5) To examine the properties of MOD-ICE for ramming experiments, a series of controlled indenter tests were performed. The two photos show the test set-up.

(6) The results of the indenter test were intriguing. For both shapes of indenter, the pressure/area plot showed relatively constant average pressures for a wide range of large areas. The pressure varied with velocity and tested to drop down to a level (shown as P_{nom}) once the velocity went to zero. (4 plots - 2 indentors, 2 ice strengths, 5 velocities each).

(7) This figure is an expanded view of five of the rams. This plot is on the same scale as the first figure (full scale MV ARCTIC data) and can be directly compared. The comparison suggests that there is room to doubt the validity of the curve fit on the full scale data. These curves show force to be proportional to indentation squared (which results in pressure independent of area).

(8) These are plots of average pressure versus velocity. This suggests that there exists a pressure which will initiate failure at zero velocity (all this P_{nom} because it is qualitatively the same as P_{nom} defined by Riska). At higher velocities, the average pressure rises, due to kinetic effects (could include viscosity, inertia).

(9) These two figures illustrate the find of error that can result if the time of contact (and indentation at time zero) was wrong, as might have happened with the full scale data. An apparent pressure versus square root of area could result.

(10) This full scale data from iceberg tests also suggests constant pressures over large areas.

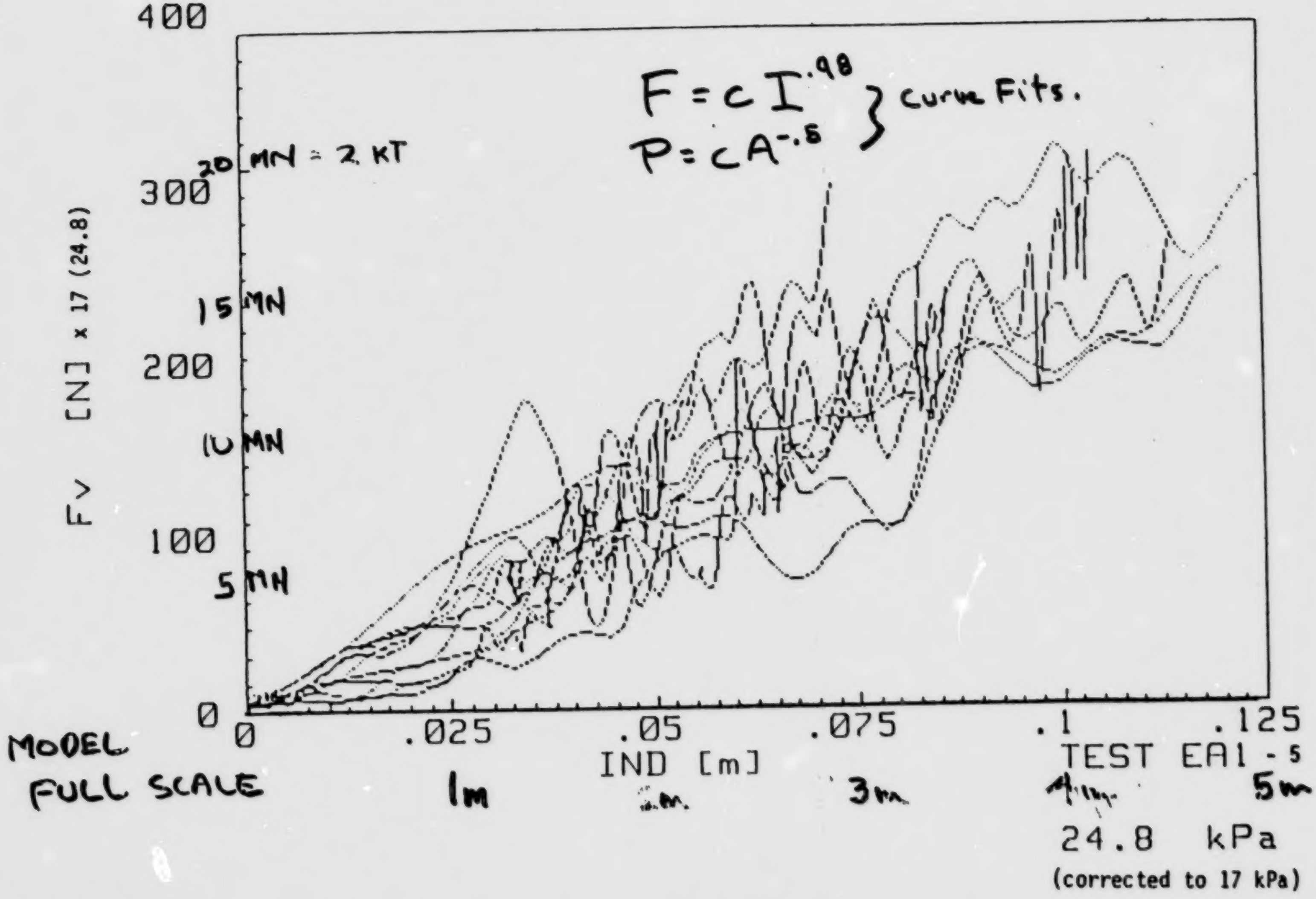
(11) A final slide. The top figure is from Dr. Riska's thesis, and represents a conceptual model for the contact process. The lower sketch is based on recent work done by Dr. Riska and a graduate student (Antti Joensuu). Their new conceptual model is one of direct ice contact in the middle of the contact zone, with extrusion in both directions. Examination of photos from the full scale MV ARCTIC ramming tests showed some evidence of a similar phenomena (a dark patch of possible intact ice near the middle of the contact zone). Similar incomplete evidence of the same phenomena has been seen in model ice ramming tests into MOD-ICE.

CONCLUSION

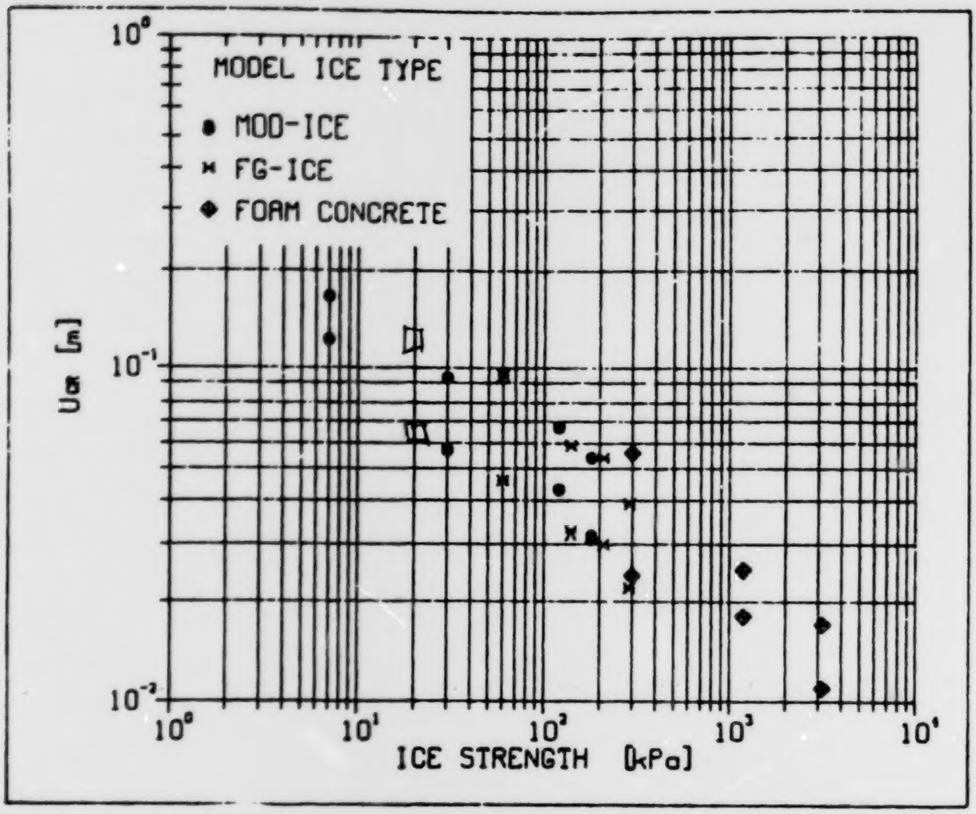
This presentation was meant to stimulate discussion rather than present a well formed theory. The question remains - What is the true nature of the ship/ice contact?

(1)

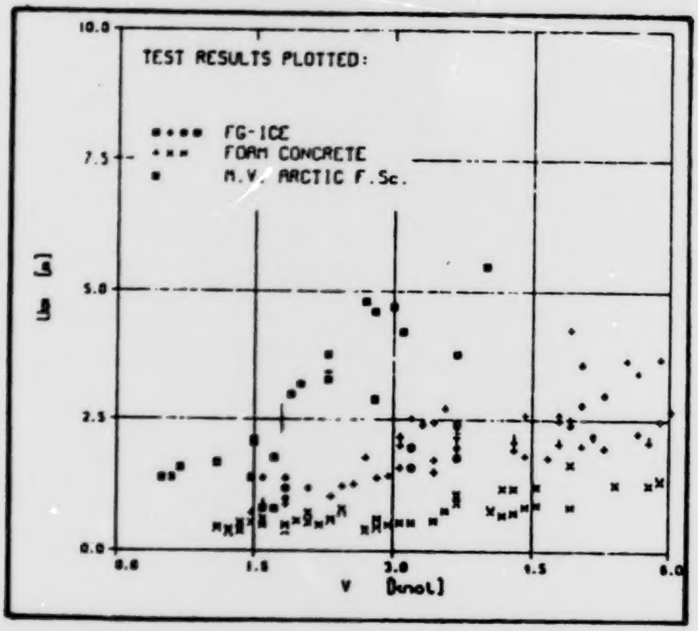
COMPARISON OF FORCE/INDENTATION TEST FOR
MODEL (RAM EA1-5 CORRECTED TO 17 kPa)
AND FULL SCALE (MV ARCTIC TRIALS 1984 [2]



(2)

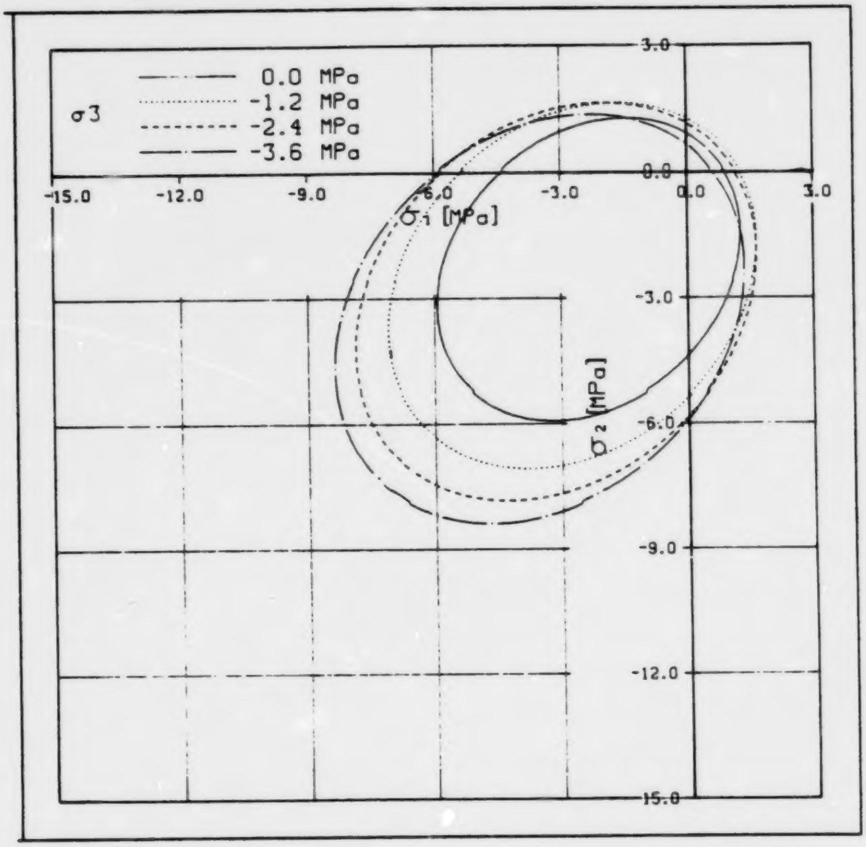


Indentations from rams with speed of 0.15 m/s and 0.30 m/s plotted versus model ice strength.

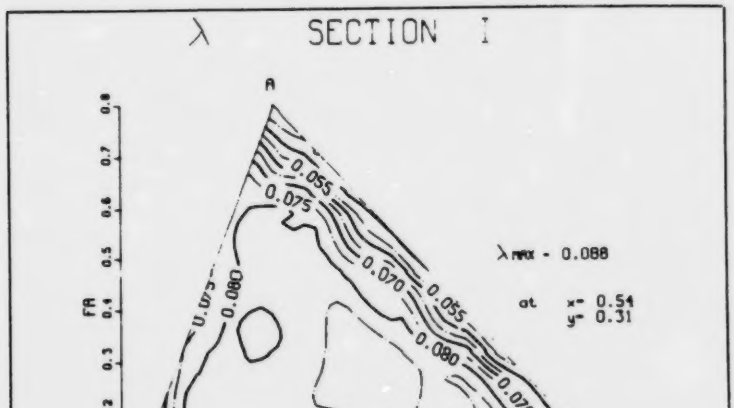


Extrapolated horizontal indentations from model tests compared with full scale values.

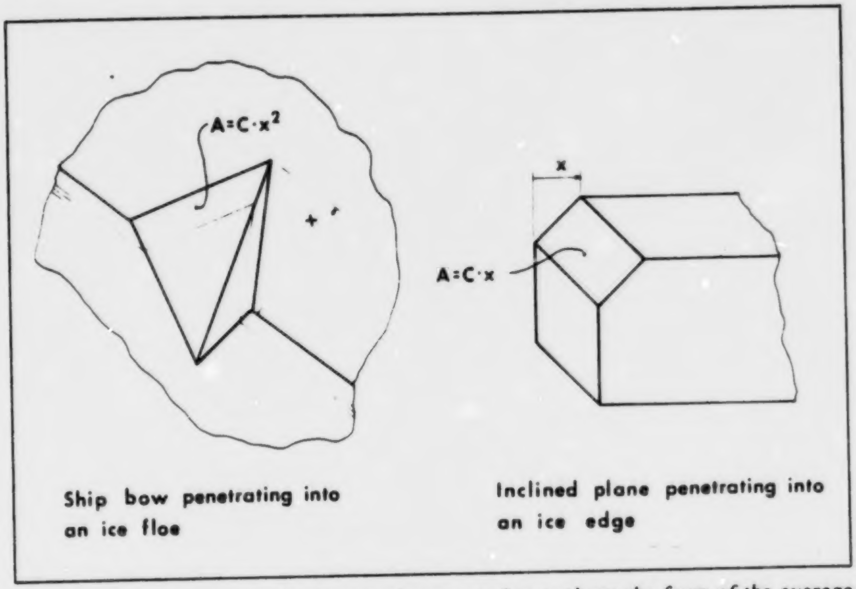
(3)



Failure surface of multi-year ice at temperature −10 °C plotted using the third principal stress as a parameter.

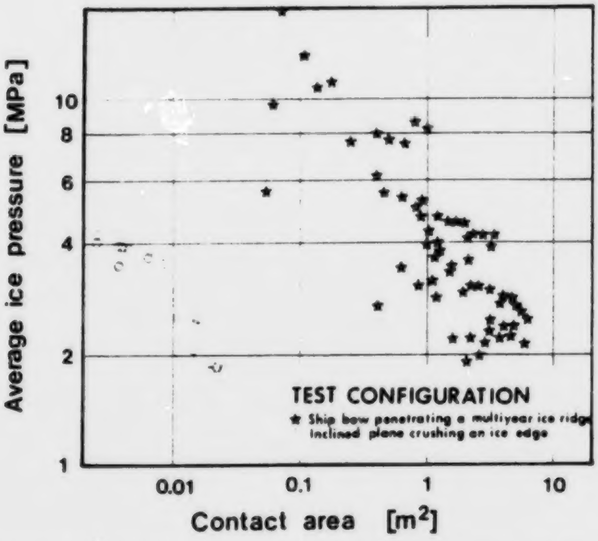


(4)


A=C·x²
x
A=C·x
Ship bow penetrating into an ice floe
Inclined plane penetrating into an ice edge

Contact geometry in the experiments used to evaluate the form of the average contact ice pressure.

30



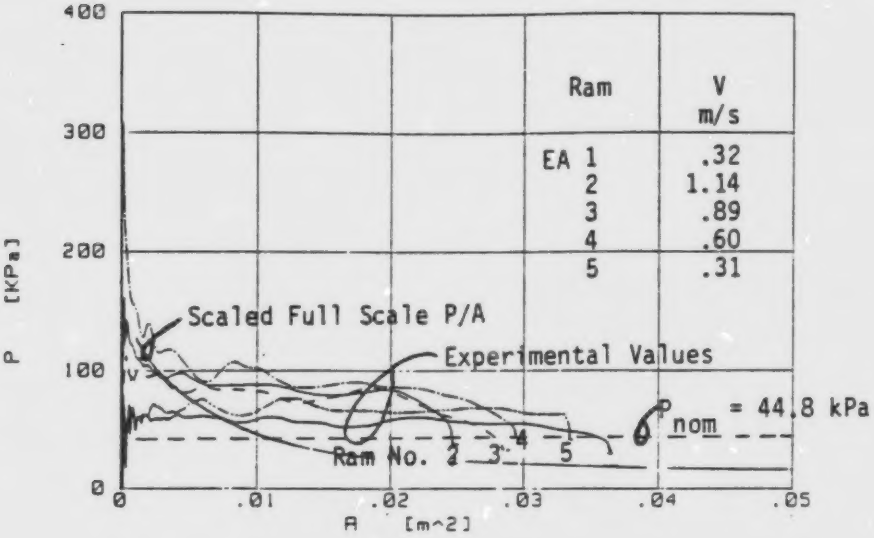
Measured average ice pressure values form two penetration tests. Results are reproduced from references /55, 68/.

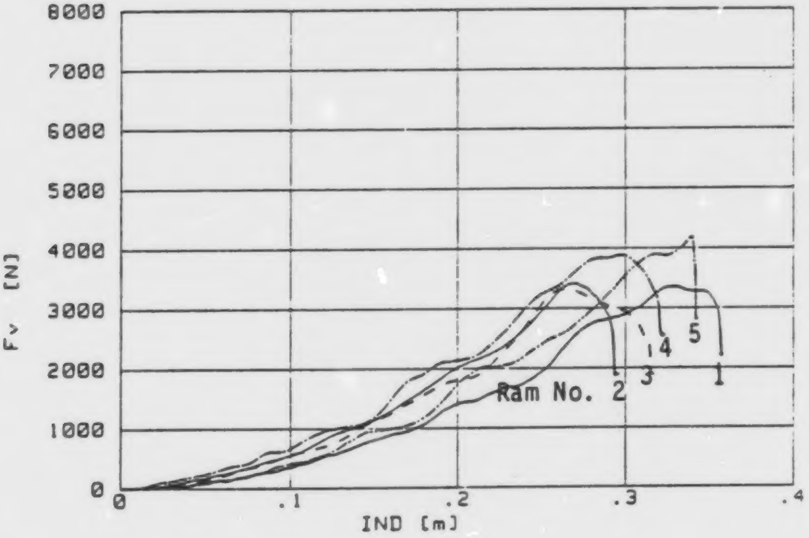
(5)

CONTROLLED INDENTER TESTS IN MOD-ICE
WITH AN INCLINED CYLINDRICAL INDENTER

CONTROLLED INDENTER TESTS
WITH AN INCLINED WEDGE INDENTER

(6)

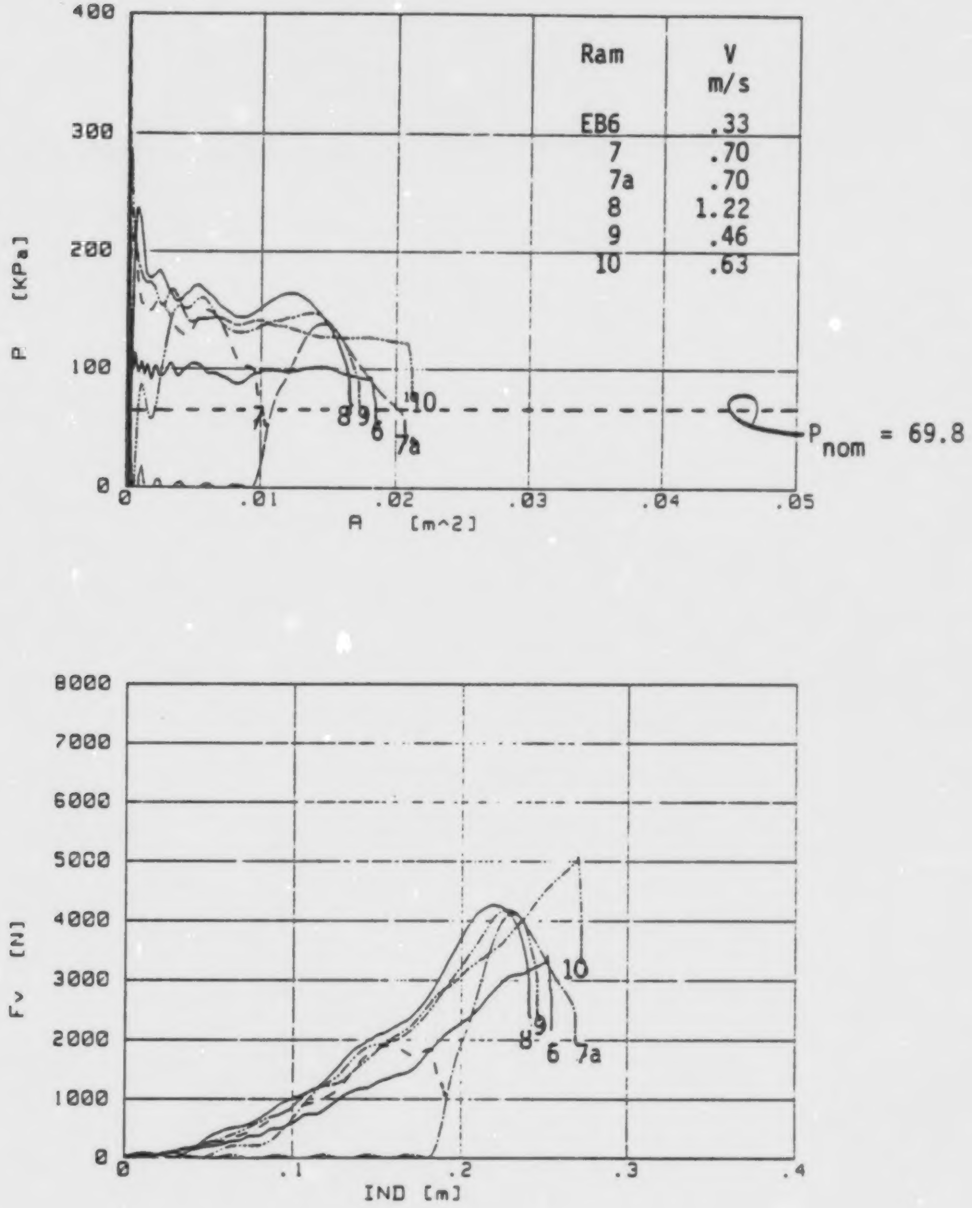




PRESSURE/AREA AND FORCE/INDENTATION PLOTS
FOR RAM EA 1-5

(WEDGE INDENTOR, 24.8 kPa ICE)

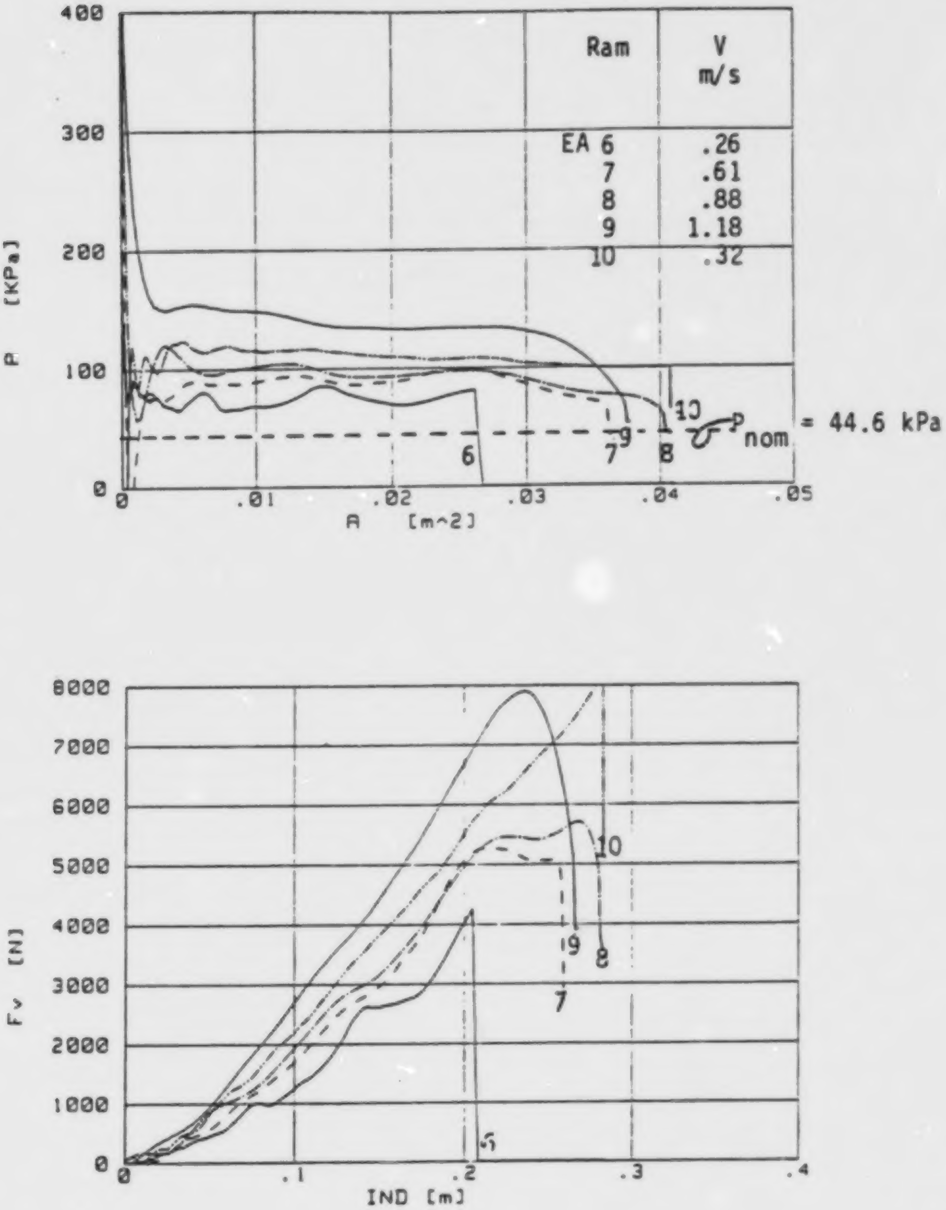
(6)



PRESSURE/AREA AND FORCE/INDENTATION PLOTS
FOR RAMS EB 6 - 10

(WEDGE INDENTOR, 38.6 kPa ICE)

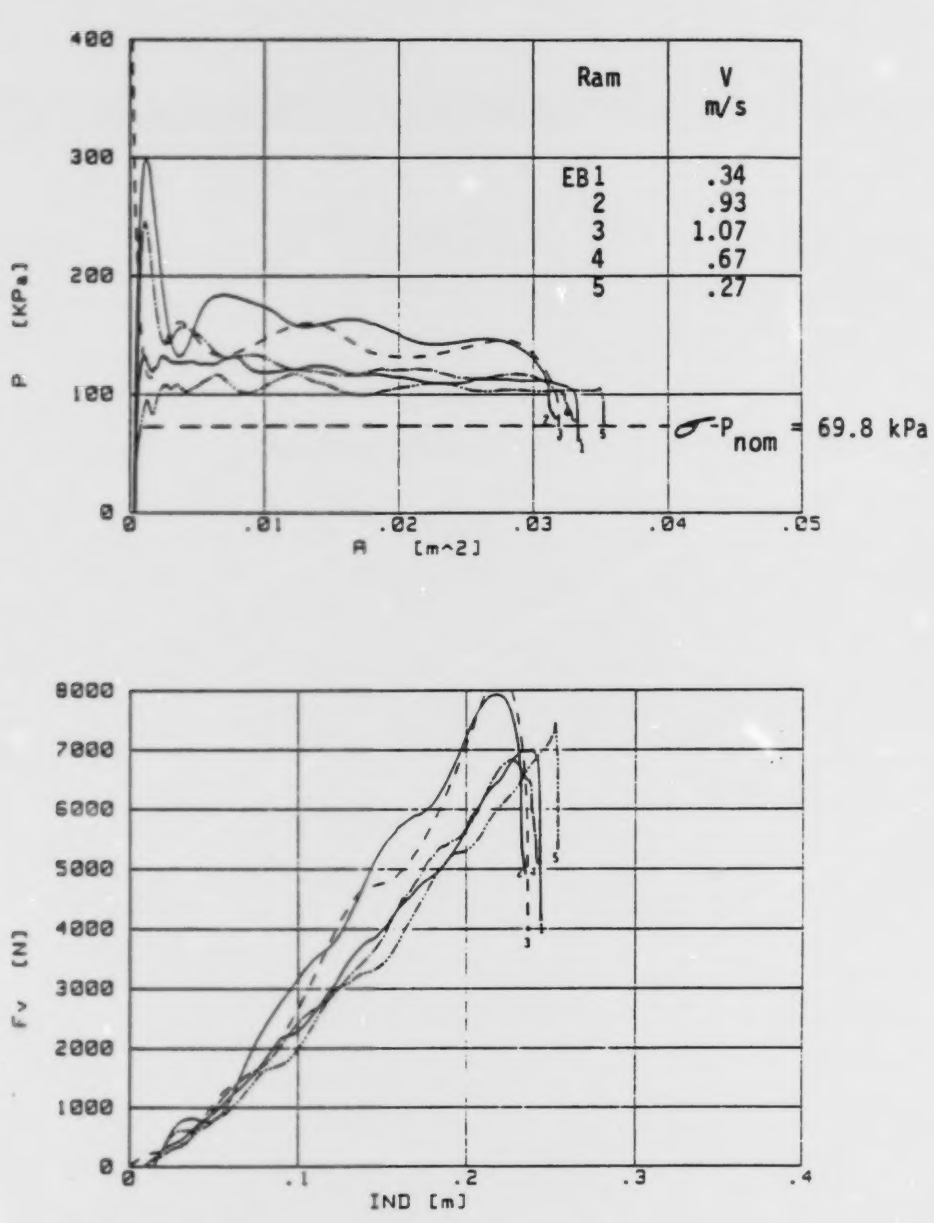
(6)



PRESSURE/AREA AND FORCE/INDENTATION PLOTS
FOR RAMS EA 6 - 10)

(CYLINDRICAL INDENTOR, 24.8 kPa)

(6)

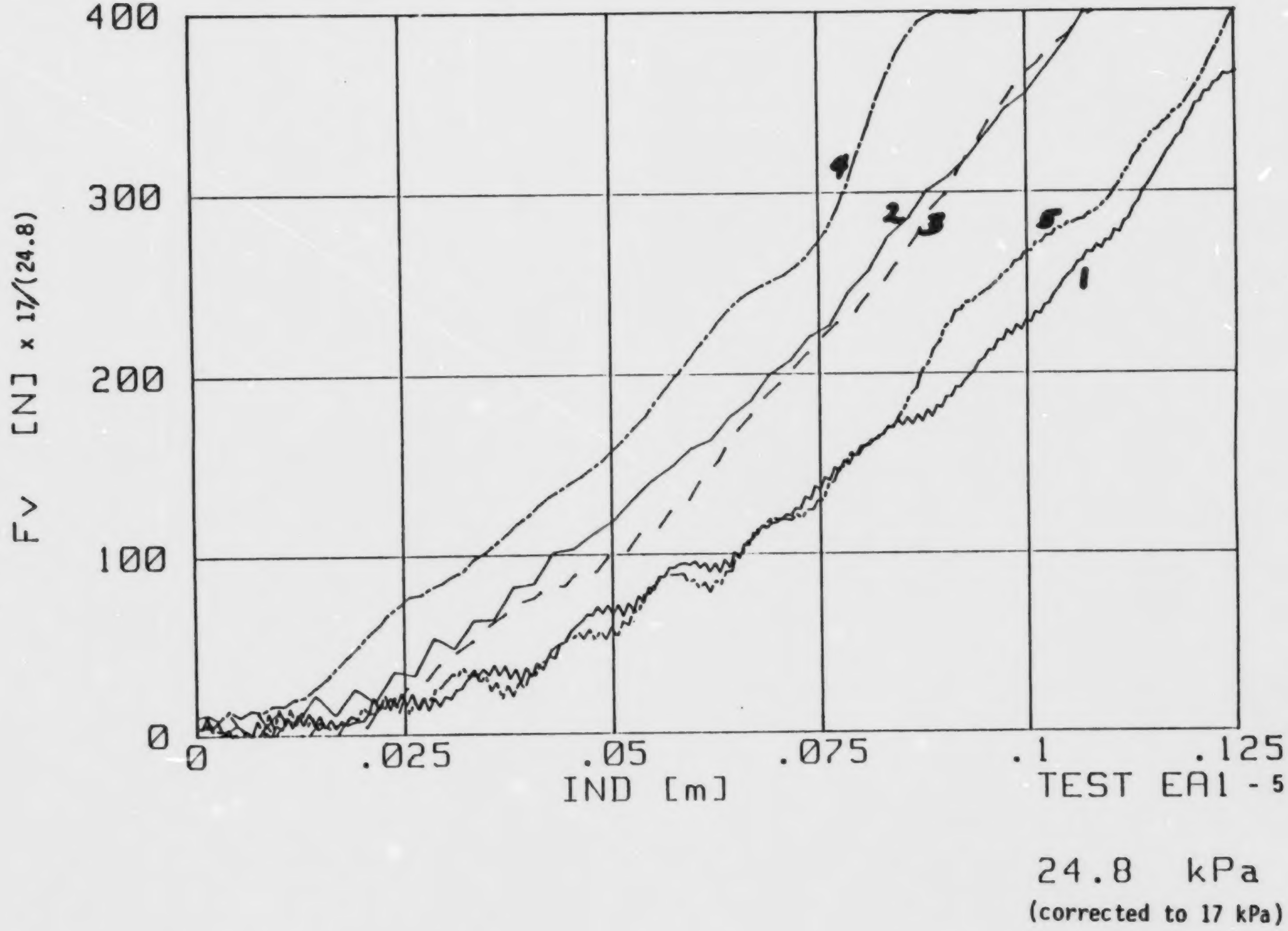


PRESSURE/AREA AND FORCE/INDENTATION PLOTS
FOR RAMS EB 1 - 5

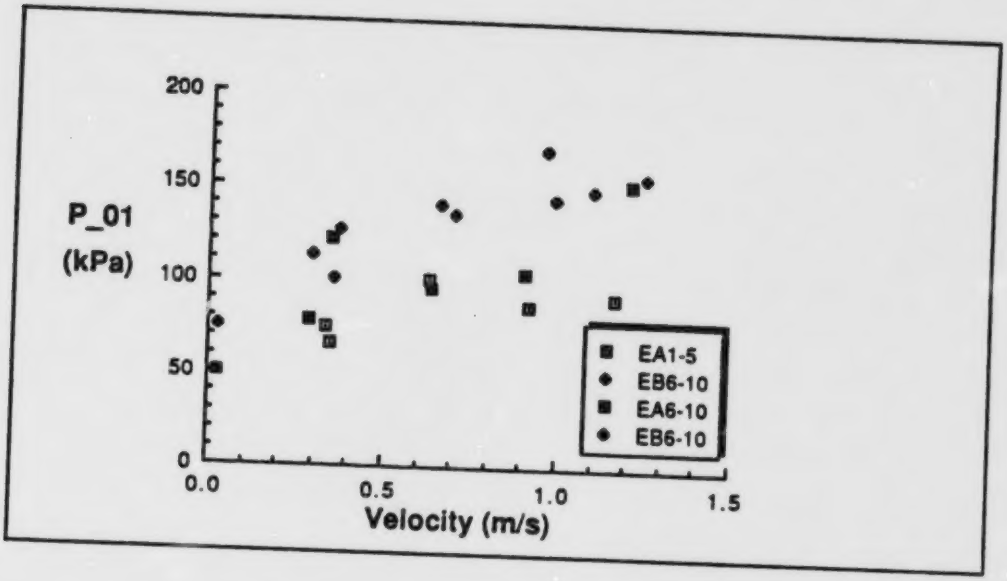
(CYLINDRICAL INDENTOR, 38.6 kPa)

(7)

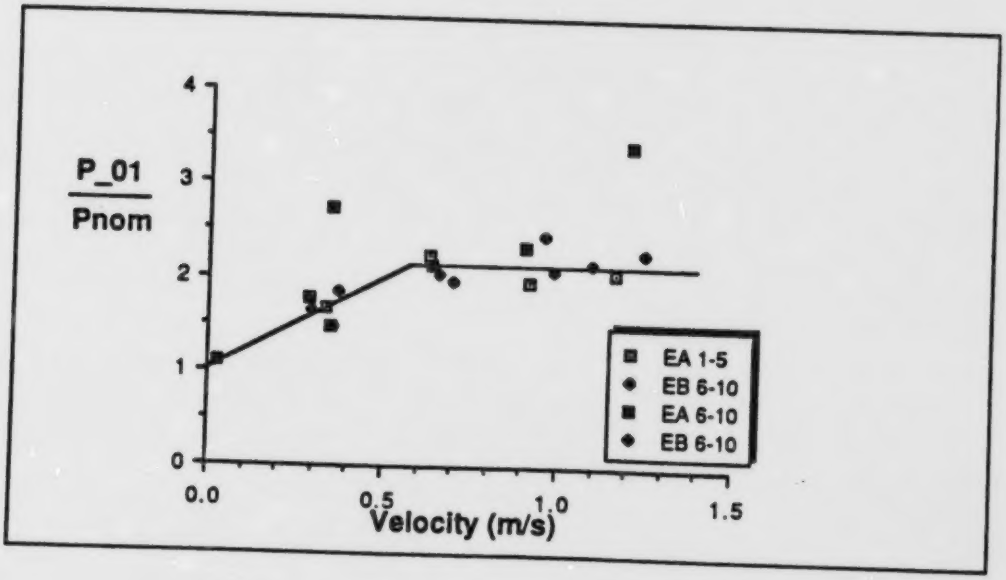
COMPARISON OF FORCE/INDENTATION TEST FOR
MODEL (RAM EA1-5 CORRECTED TO 17 kPa)
AND FULL SCALE (MV ARCTIC TRIALS 1984 [2]



(8)

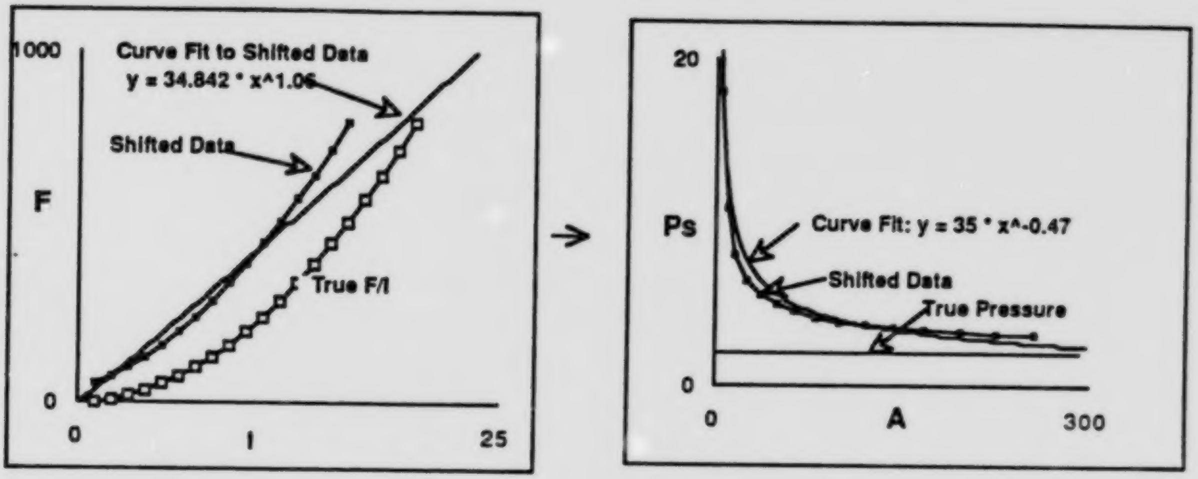


PRESSURE (AT .01m^2) VERSUS INDENTOR VELOCITY



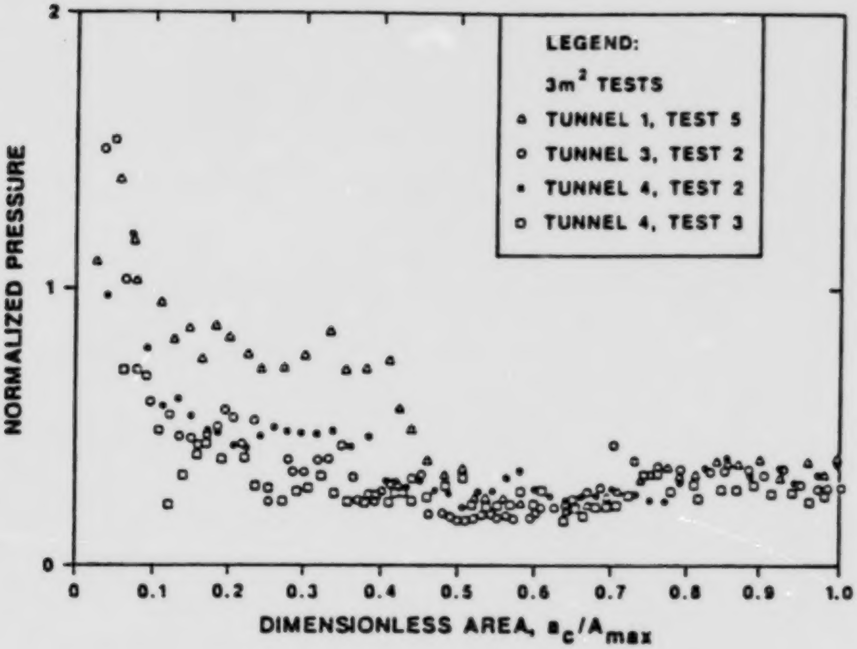
NONDIMENSIONAL PRESSURE (AT .01 m^2) VERSUS VELOCITY

(9)



THE CONVERSION OF A 'FITTED' FORCE/INDENTATION TO PRESSURE/AREA

(10)



DIMENSIONLESS PRESSURE/AREA PLOTS
FOR $3m^2$ INDENTOR TESTS IN ICEBERGS
TAKEN FROM [16]

(11)

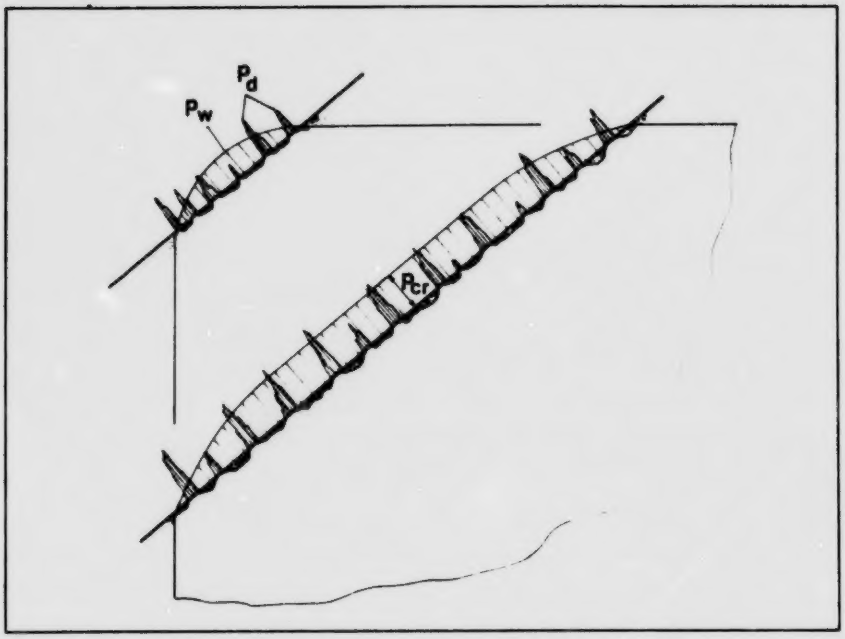
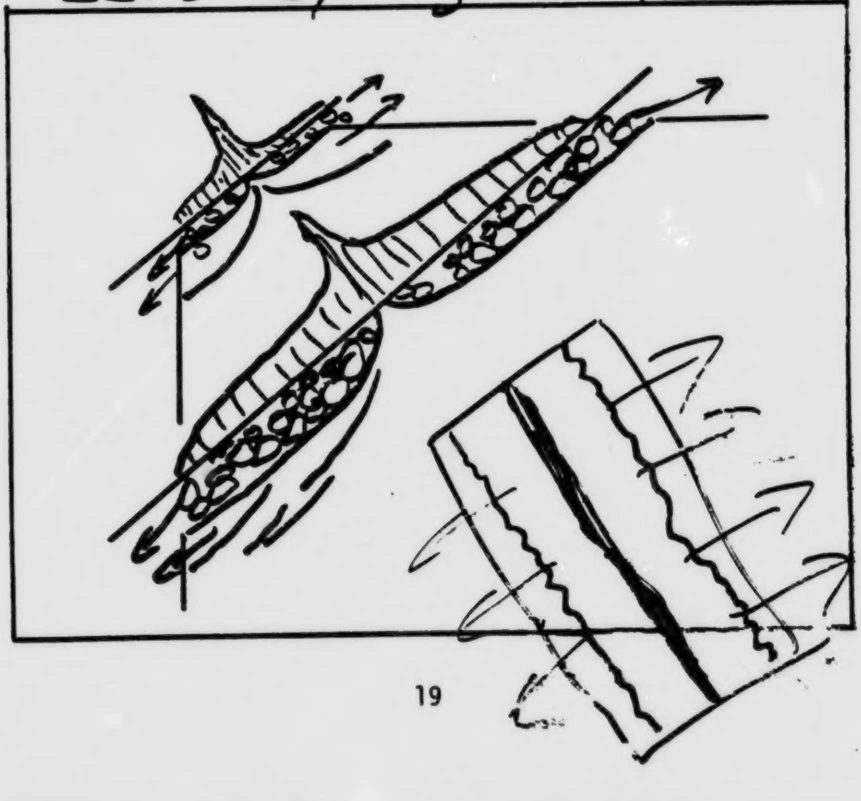


Fig. 11. The development of the direct contact pressure p_d and that in the layer of crushed ice p_w during the penetration into ice. p_{cr} is the pressure required to break the ice under the layer of crushed ice.

TESTS By Kaj Riska, Antti Joensuu at TKK



METHODS OF ADDRESSING VESSEL PERFORMANCE IN SNOW-COVERED FAST ICE AND PACK ICE

PAPER PRESENTED AT
WORKSHOP ON ICE PROPERTIES
C-CORE JUNE 21/22, 1988

BY
R.J. GILL, ACRES INTERNATIONAL LIMITED
ST. JOHN'S, NEWFOUNDLAND

ABSTRACT

Simple techniques to analyze the performance of vessels in snow-covered fast ice and pack ice are presented and comparisons made with observations from six icebreaking probes to Lake Melville, Labrador from 1980 to 1983. Nominal power requirements for icebreaking vessels of various sizes are also determined.

INTRODUCTION

During the winters of 1980 to 1983 inclusive, six icebreaking probes were conducted into Lake Melville, Labrador (Figure 1). These probes were part of a series of studies undertaken to determine the technical and economic feasibility of winter shipping to Labrador and to define the ice regime both in the lake and the offshore pack. Five of these probes were conducted with the Canadian Coast Guard icebreaker Sir John Franklin. The other probe was conducted with the icebreaking bulk carrier M.V. Arctic as the primary test vessel accompanied by the Sir John Franklin as a support icebreaker. The participants in these probes were

- Department of Development - Government of Newfoundland and Labrador
- Department of Regional Economic Expansion - Government of Canada
- Canadian Coast Guard
- Transportation Research and Development Centre
- National Research Council
- Atmospheric Environment Service

- Canada Centre for Remote Sensing
- Arctic Pilot Project
- CN Marine
- Northwater Navigation Limited
- Canarctic Shipping Limited
- C-CORE.

Reports of each of the probes were prepared by the respective consultants referenced at the end of this paper.

In 1983, Acres was contracted by the Department of Development to provide an overview analysis of vessel performance during the probes. (Acres 1984). The speed of the vessels through known ice and snow conditions, the transit time through the pack ice and ridged fields, and the results of various maneuvering tests were addressed in that report. Where possible, comparisons were made with the theoretical predictions form ice resistance theory for movement through a continuous cover, and these predictions were also used to arrive at nominal power requirements for a range of icebreaking cargo vessels. The effects of transit through snow covered ice and refrozen tracks were also addressed and were quantified where the data permitted. In some cases, insufficient data existed to carry out a quantitative analysis; this was particulary true in the case of vessel performance in refrozen tracks and to a lesser extent in ridged ice and pack ice.

In this paper, consideration is given to simple techniques of addressing vessel performance in snow-covered fast ice and in pack ice and to estimating vessel power requirements.

SNOW COVERED FAST ICE

The curves shown in Figure 2 are derived from the work of Enkvist (1972) and incorporate the specifications of the Sir John Franklin. The Enkvist equation may be broken into three parts each of which is associated with a component of the ice resistance. These parts are the ice resistance associated with

- the actual breaking of the ice sheet
- the submergence of the broken ice pieces
- the movement of ice pieces past the hull of the vessels.

Using appropriate values for ice properties and vessel bow angles, the total resistance, for the Franklin is simplified to

$$R_T = 0.17\ BHh + 0.14\ Bh + 1.8\ Bh^2 + 0.13\ Bhv^2$$

where

R_T = resistance (tonnes)
B = beam (m)
H = draft (m)
h = ice thickness (m)
v = speed (m/s)

The following values for ice properties were used.

Flexural strength σ_f = 350 kPa (50 psi) (as determined from tests during the probes).
Strength to modulus ratio = $\sigma f/_E = 1.8 \times 10^{-4}$

Ice density $\rho i = 945\ kg/m^3$

Coefficient of friction between ice and hull = 0.1 (an average value taken from the literature).

The speed that the vessel can maintain in given ice conditions is determined by the thrust of the engines which may be related to speed by the following equation (from Johansson, 1977).

$$T = T_o \left[1 - \frac{v}{3v_o} - \frac{2v^2}{3v_o^2} \right]$$

where

T - thrust at speed (v)

T_o - thrust at zero speed (bollard pull)

V_o - maximum open water speed of vessel.

For the Sir John Franklin $T_o = 122$ tonnes at full power and $V_o = 8.3$ m/s; hence $T = 1.22 - 4.9\ v - 1.2\ v^2$. Since the required thrust at any speed can be related to the associated ice resistance, the speed for any ice thickness may be calculated.

Naturally, the resulting curve of speed versus ice thickness and the agreement with actual values depend on the choice of parameter values. The ship parameter values are essentially fixed so that any uncertainty is mainly associated with the choice of ice parameter values, although the coefficient of friction between ice and hull actually is determined by both vessel and ice characteristics. Since this coefficient depends not only on the surface finish of the hull, but also the speed of the vessel and to some extent whether the ice is snow covered, one can only choose a reasonable average from the values quoted in the literature, unless measurements are actually made during the testing. Here a value of 0.1 is used.

To allow for the extra resistance presented by snow, the resistance equation was modified by assuming that the primary effect would be evident in the submergence term rather than the other two terms. It is doubtful that a snow cover would increase the actual icebreaking component of resistance, and while some effect would be felt in the velocity dependent component, calculations showed it to be fairly insignificant. For example, if it is assumed that the frictional effects of the snow would be evident in the latter component and that the snow were to double the coefficient of friction (from 0.1 to 0.2), the decrease in speed in ice 1.0 m thick would be less than 1 knot and at smaller thicknesses the difference would be less than this.

However, if the buoyancy effects of the snow are considered and are included in the submergence term, it can be shown that the increase in resistance in this component is substantial for the large snow thicknesses that often exist in late winter.

The submergence term in its basic form is

$$R_s = 2g\rho_{\Delta_i} B h_i H \left(\eta_{sp} + \frac{L_E}{H}\eta_{s\mu E}\right)$$

where

ρ_{Δ_i} = density difference in ice and water
h_i = ice thickness
B, H, L_E, $\eta_{s\mu E}$ relate to ship parameters

Adding snow effects (h_s, $\rho_{\Delta s}$) gives

$$R_s^1 = 2gBH \left(\eta_{sp} + \frac{L_E}{H}\eta_{s\mu E}\right)\left(\rho_{\Delta i}\, h_i + \rho_{\Delta s}\, h_s\right)$$

$$\frac{R_s^1}{R_s} = \frac{\rho_{\Delta i} h_i + \rho_{\Delta s} h_s}{\rho_{\Delta i} h_i} = 1 + \frac{h_s}{h_i}\,\frac{\rho_{\Delta s}}{\rho_{\Delta i}}$$

$$= 1 + k_1\, k_2$$

where $k_1 = \frac{h_s}{h_i}$ and h_s = snow thickness
h_i = ice thickness

k_2 = constant which is determined by the snow density. As the density increases, k_2 decreases.

For dry snow with a specific gravity of 0.1 (say) and thickness equal to one-half the ice thickness,

$$R^{1}_{S} = 5.5\ R_s$$

From Figure 2, it is seen that the effect of this increased resistance at an ice thickness of 0.75 m, for example, is to reduce the vessel speed by about 70 percent. Figure 2 also suggests that a vessel of the Sir John Franklin's capability could not progress continuously in ice about 0.80 m thick with 0.40 m of dry snow. As the snow density increases, the force required to submerge the ice becomes less and the vessel capability becomes greater. In this case, however, the snow may be sticky and result in higher friction forces on the vessel and a larger contribution to overall resistance from the velocity dependent term.

The two data points obtained from the NRC dedicated trials of the vessel during the 1980 probes are useful for assessing the accuracy of this equation (Michailidis and Murdey, 1981). In the January probe, the speed at approximately full power in ice 0.67 m thick with 0.12 m of snow was 8.2 knots. No snow density measurements were made but at that time of the year, the snow was dry and the specific gravity was probably around 0.1. The speed calculated from the resistance equation is thus 7.8 knots for a difference of 0.4 knots from that actually experienced. During the dedicated trials of the March probe, the vessel speed was determined to be 3.5 knots in ice 0.74 m thick and covered with snow 0.52 m thick over the test run at full power. The snow at this time was wet and probably had a specific gravity of at least 0.3. Using these figures in the resistance equation results in a speed of 1.9 knots so that the equation under predicts the actual speed for these conditions. The greatest uncertainty here is associated with the snow density which has a large effect at such low speeds. If the snow specific gravity were 0.4 instead of 0.3, the calculated speed would then be identical to the actual speed.

While the values from the dedicated trial runs are the best test of the theoretical predictions, some discussion is appropriate here on the other data points shown in Figure 2. As stated previously, these are not as reliable in evaluating performance because ice and snow measurements were made at large intervals and these spot measurement are applied over the total interval. There will be variations in the ice and snow conditions over the interval which could lead to an average thickness somewhat different that measured at only one or two locations in the interval. In any case, some general comparisons may be made between results for probes during approximately similar times of the winter.

The uniform ice thickness during the January 1982 probe was about 20 percent less than that during the January 1980 probe and snow thickness was also somewhat less during 1982. The average speed calculated during the 1982 probe is about 1 knot higher than the theoretical prediction and 2 to 4 knots higher than the speeds experienced during the 1980 probe. One might be tempted to suggest that the low friction coating on the vessel during the latter probe was responsible for this improvement in speed; however, a comparison of the March probes for 1980 and 1982 does not show an improvement in speed during the later probe although ice and snow conditions in the undeformed areas were similar. It is, of course, possible that the benefits of a reduction in frictional properties becomes masked at lower speeds when, as discussed previously, the increased resistance due to snow overrides any reduction in frictional resistance.

PACK ICE

Although the variation in pack ice features makes it difficult to formulate relationships between vessel progress and ice conditions in the pack, an attempt was made to establish a tentative relationship. Because both the ice concentration and thickness determine the ice resistance in the pack, the data are shown in Figure 3 in the form of vessel speed versus an ice index which is the product of thickness and concentration. Here the concentration is measured in tenths and the thickness in metres.

A theoretical curve is also shown in Figure 3. This curve has been deduced by assuming an equation of the following form.

$$\frac{v^2}{v_o^2} + \frac{i^2}{i_o^2} = 1$$

where

v = vessel speed in ice
v_o = maximum open water speed
i = ice index
i_o = ice index which results in zero speed.

The value for i_o has been determined by assuming that the ice thickness that results in zero speed is equal to that determined from the Enkvist equation for a continuous ice cover (Figure 2) and by assuming that 10/10 coverage is similar to a continuous ice sheet. However, in all likelihood, the speed in pack ice with 10/10 concentration and negligible pressure would be greater than in a continuous fast ice cover of similar thickness because of weak zones which exist at the edges of the floes in the pack, the nonhomogeneity of the ice and the possibility of failure by splitting rather than bending. However, from the experience on these probes, it appears that the Enkvist equation may overpredict the ice thickness which would result in zero speed and this would tend to compensate to some extent. By the same argument, pressure in the pack ice would tend to reduce this thickness, and this can be seen in Figure 3 since if the curve were fitted more closely to the data points, it would cross the ice index axis at a lower value. The main reason for using an index related to the speed in a continuous cover is that the relationship can be generalized and the method applied to other icebreaking vessels since only the maximum open water speed and the ice thickness resulting in zero speed need be known.

Exploring this further, one may write the equations for the Sir John Franklin and the M.V. Arctic as follows

Sir John Franklin:

$$v^2 = 256 \, [1 - 0.00416 \, c^2h^2]$$

where

c = concentration
h = thickness

M.V. Arctic:

$$v^2 = 249 \, [1 - 0.0051 \, c^2h^2]$$

The formula for the Sir John Franklin is plotted in Figure 4 for three concentrations. Less accuracy can be expected as the concentration is decreased since the vessel speed will approximate the open water speed once the concentration is less than 8/10, even at large thicknesses.

IMPLICATIONS FOR VESSEL REQUIREMENTS

The results of the probes to Lake Melville, together with theoretical considerations, may be used to help determine the capability of vessels required for winter navigation in the area.

In Figure 5, the power requirements are plotted as a function of ice thickness for four icebreaking vessel sizes and a speed of 4 knots. A snow cover equal to 0.3 times the ice thickness is also assumed. These curves are based on the Enkvist resistance equation and use bow angles equivalent to those of the M.V. Arctic. Ice strength, modulus, and friction values are as assumed previously. To obtain power from resistance, a typical ratio of bollard pull to power of 0.1 t/hp is used. The values of vessel parameters such as length, beam and draft are typical for the tonnages considered here with modification for icebreaking considerations. These values have been taken from a previous report to the Department of Development (Acres/NORDCO 1982).

While these calculations are theoretical, they are presented here to serve as an indication of the typical powering one would have to consider for operating in Lake Melville. From the comparisons of theoretical and actual vessel speed presented in Figure 2, it appears that the resistance experienced by the vessels is greater than that predicted by the equation without a modification for snow; therefore, the predicted power in ice without snow would be less than that actually required to operate at the same speed. On the other hand, a comparison of actual vessel progress through snow-covered ice with theoretical predictions indicates that the vessel speed may be underpredicted. Therefore, the curves shown here may be an overprediction of the power requirements for these conditions. These curves should then be considered to represent an upper limit for vessel powering for late winter conditions on Lake Melville.

ACKNOWLEDGEMENT

Permission by the Department of Development and Tourism, Government of Newfoundland and Labrador to present this paper and the support of Acres International Limited are gratefully acknowledged.

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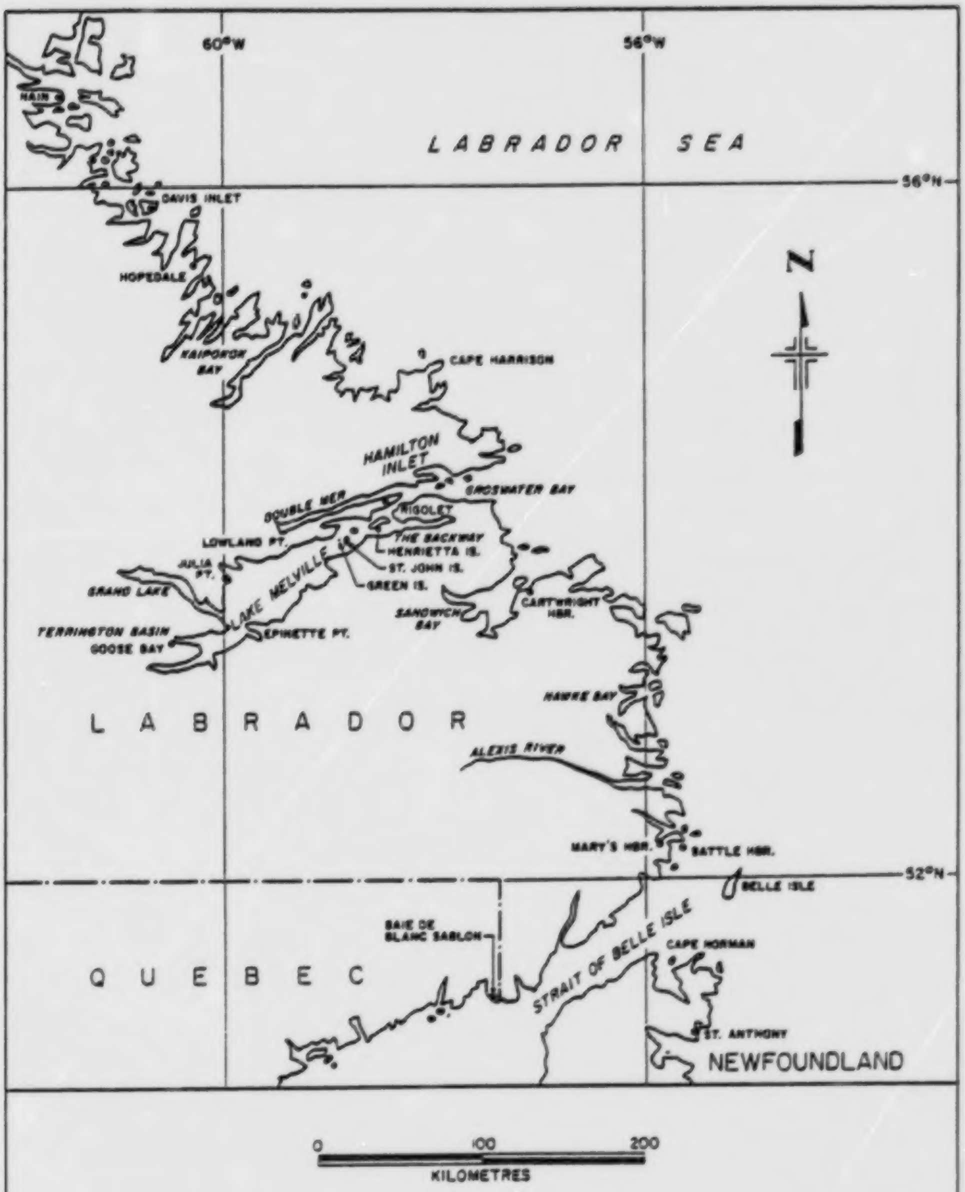

60°W
56°W
NAIN
LABRADOR SEA
56°N
DAVIS INLET
HOPEDALE
N
KAIPOKOK BAY
CAPE HARRISON
HAMILTON INLET
GROSWATER BAY
DOUBLE MER
RIGOLET
LOWLAND PT.
THE BACKWAY
HENRIETTA IS.
ST. JOHN IS.
GREEN IS.
JULIA PT.
LAKE MELVILLE
GRAND LAKE
TERRINGTON BASIN
GOOSE BAY
EPINETTE PT.
SANDWICH BAY
CARTWRIGHT HBR.
HAWKE BAY
LABRADOR
ALEXIS RIVER
MARY'S HBR.
BATTLE HBR.
52°N
BELLE ISLE
BAIE DE BLANC SABLON
STRAIT OF BELLE ISLE
CAPE NORMAN
QUEBEC
ST. ANTHONY
NEWFOUNDLAND
0
100
200
KILOMETRES

FIG. 1

LAKE MELVILLE AND APPROACHES TO HAMILTON INLET

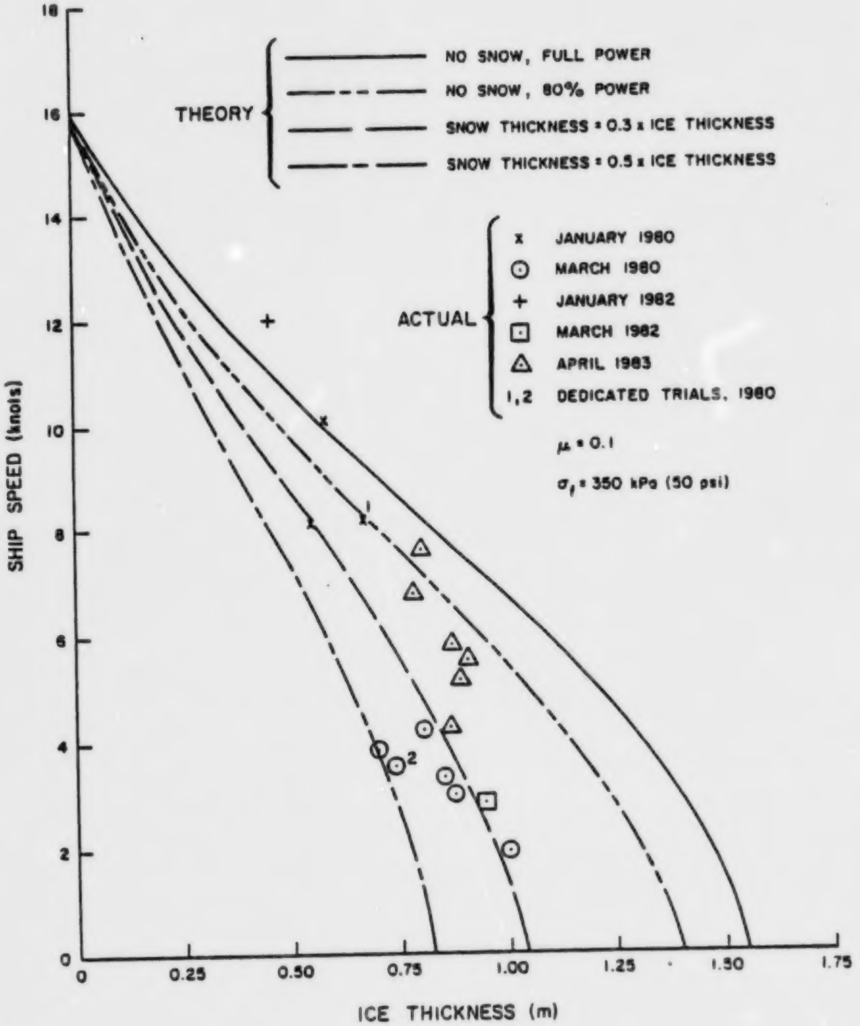


FIG.2

SPEED OF SIR JOHN FRANKLIN IN UNIFORM ICE

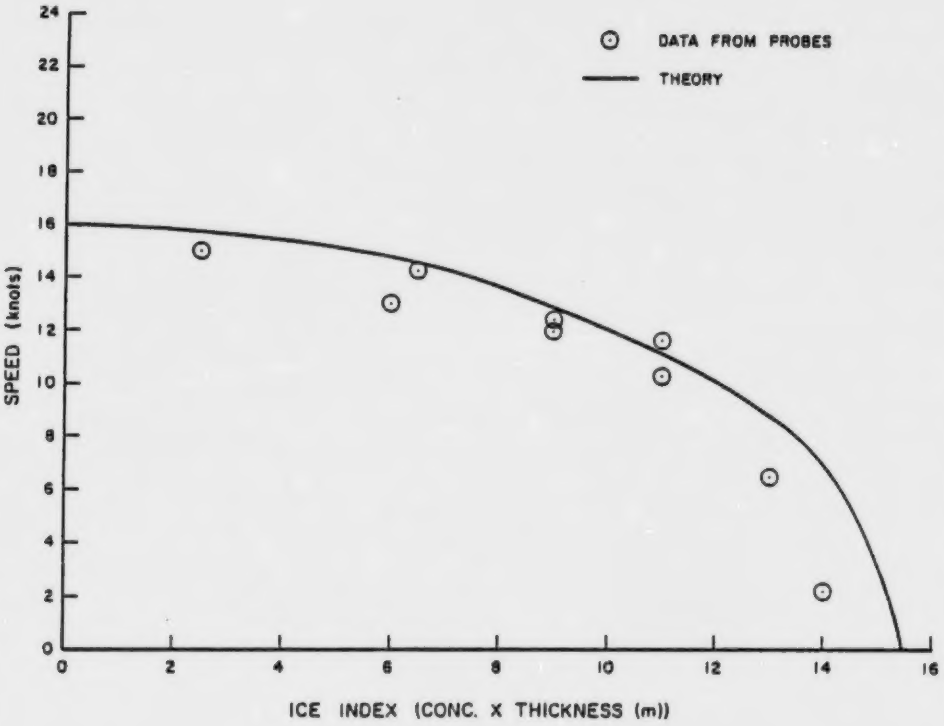


FIG. 3

SPEED VS. ICE INDEX FOR SIR JOHN FRANKLIN IN PACK ICE

ACRES

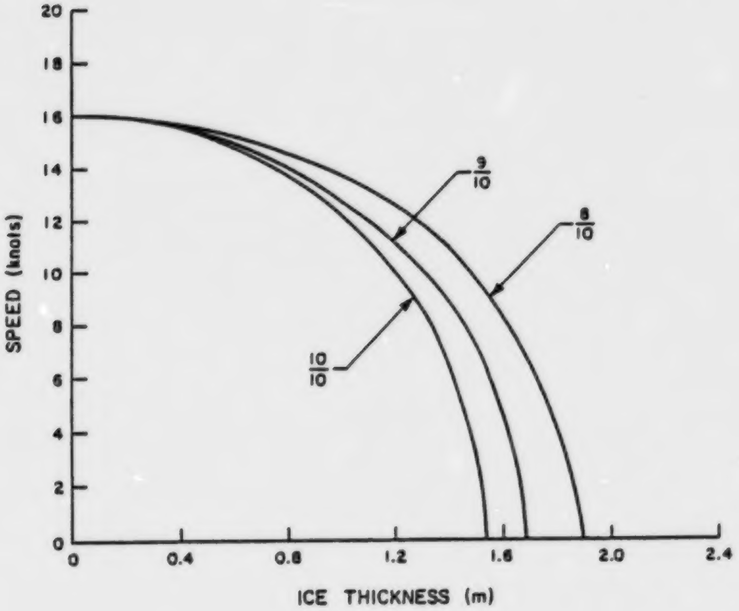


FIG. 4

SIR JOHN FRANKLIN SPEED
VS. ICE THICKNESS FOR VARIOUS CONCENTRATIONS

ACRES

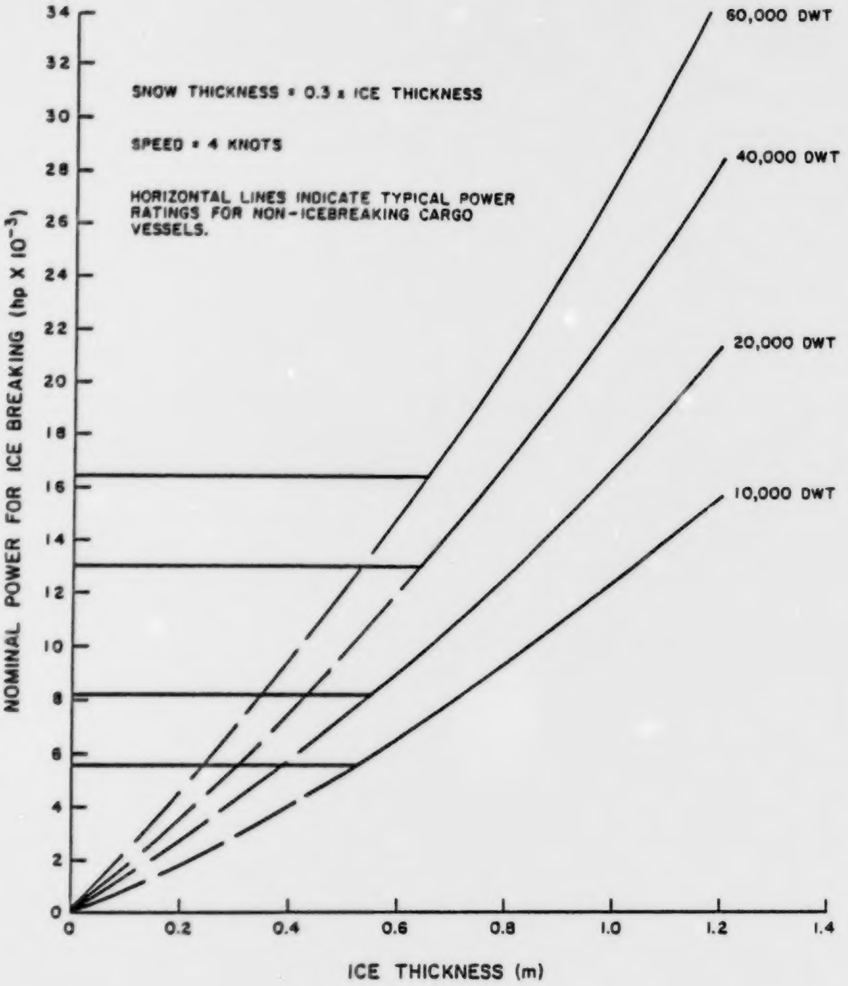


FIG. 5

NOMINAL POWER FOR ICEBREAKING VS. ICE THICKNESS

A Review of Field Observations

# of Ice Failure Modes

Dr. M. Metge, CANATEC, Calgary

This presentation was mostly a visual one, where slides were shown of different ice failure modes as observed during actual ice events in the field. Examples of ice interaction with structures such as Hans Island, Katie's Floeberg, Tarsiut Island, the Molikpaq, the SSDC and Issunguak island were shown. These pictures were used to give examples of the different failure modes identified in Figure 1.

Examples of "single floes", "multiple floes", "floe in sheet" and "structure frozen in" types of scenarios were shown and discussed.

Two new major ice failure modes have been introduced to describe the observations made mostly during the multi-year ice impacts on the Molikpaq:

- Crushing with extrusions
- Crushing with pulsations

"Crushing with extrusions" is used to describe the case where ice not only fails in "pure crushing" (i.e. very small blocks relative to the ice thickness) but also the crushed ice forms a kind of "toothpaste" which gets extruded upwards at the ice-structure interface.

"Crushing with Pulsations" is used to describe the case where the ice failure occurs in cycles of loading, failure, extrusion and unloading as shown in Figure 2. An important characteristic of this type of failure mode is that the ice seems to fail simultaneously across the whole contact area.

DATA SET:

ICE FAILURE MODES

SCENARIOS	ICE TYPES		LIMIT STRESS											LIMIT FORCE						
			CRUSHING (incl. Flaking & Spalling)	CR. + EXTRUSIONS	CR. + PULSATIONS	CR. into PILE-UP	MIXED MODE (CR + FLEX, Pile-up etc)	FLEXURE	RIDE-UP	PILE-UP	BUCKLING	CREEP		FLOE BREAK-OUT	RIDGING (at edge of Floe)	FLOE CRACKING	FLOE SPLITTING	LIMIT MOMENTUM (partial envelopmt)	FLOE STOPPED, ENVIR. FORCES ONLY	
SINGLE FLOE (open water)	FY	Sheet																		A
		Ridge																		B
	MY	Sheet																		C
		Ridge																		D
			☒	☒	☒	☒	☒	☒	☒	☒	☒	☒		☒	☒	☒	☒	☒	☒	
MULTIPLE FLOES (partial ice cover)	FY	Sheet																		E
		Ridge																		F
	MY	Sheet																		G
		Ridge																		H
			☒	☒	☒	☒	☒	☒	☒	☒	☒	☒		☒	☒	☒	☒	☒	☒	
FLOE IN SHEET OR PACK (full ice cover)	FY	Sheet																		I
		Ridge																		J
	MY	Sheet																		K
		Ridge																		L
			☒	☒	☒	☒	☒	☒	☒	☒	☒	☒		☒	☒	☒	☒	☒	☒	
STRUCTURE FROZEN-IN OR BREAK OUT	FY	Sheet																		M
		Ridge																		N
	MY	Sheet																		O
		Ridge																		P
			☒	☒	☒	☒	☒	☒	☒	☒	☒	☒		☒	☒	☒	☒	☒	☒	
ICE ISLAND IMPACT	Ice Island																			Q
	Isl. Fragmt																			R
ICEBERG IMPACT	Iceberg																			S
	Growler																			T
			A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	

Figure 1 TABLE OF SCENARIOS, ICE TYPES & FAILURE MODES

From "A Large Scale Ice-Structure Interaction Data Base" by Metge 'et al.' to be presented at the 1988 IAHR Conference, in Japan.

In general, crushing with extrusions leads to higher global ice loads and higher ice pressures than usual crushing failure mode. Loads due to crushing with pulsations are even higher than for crushing with extrusions. The reasons for this are complex; part is due to the simultaneous nature of the load, but part may also be due to the strain rate effect on ice strength.

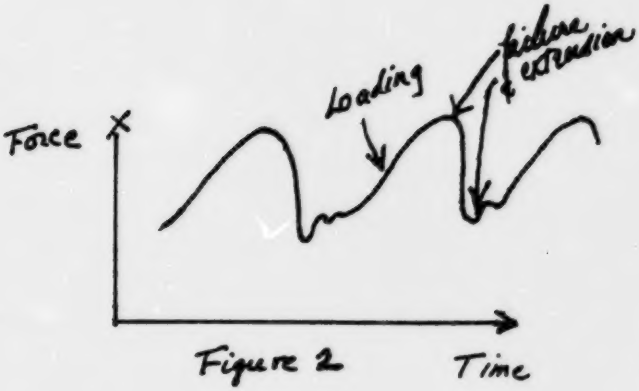


Figure 2

Session 1 - Discussion

The following questions, answers and comments formed part of the discussion period in Session 1.

H. El-Tahan:

We have seen many "standard" graphs that show that the contact area significantly affects strength. Strength was shown to vary by at least one order of magnitude with moderate change in area. Today we were shown some data that suggests that strength varies slightly with area. Does this apply to a small range of area or does it apply for certain problems only?

Does this suggest that the we can assume constant strength during a particular process even if it involves large variation of area?

I would appreciate it if this problem is given some discussion by the participants.

Thanks.

M. Metge:

This is an excellent question which is still the subject of much debate and is extremely important when we want to extrapolate existing data to much larger areas. This is necessary for instance when designing production platforms which are larger and designed for rarer events than exploration structures.

My opinion is that when designing structures where people will risk their lives, we should not use general strength versus area curves which extend over 10 orders of magnitude without some very careful scrutiny.

There are cases when we know that area alone is not sufficient to explain the change in pressure. With very narrow structures, for example, the aspect ratio effect seems to be dominant.

I believe that the best way to handle this is to recognize that both ice thickness T and structure width D have an effect, and that the relationship between ice pressure P with D and t may change with failure mode. For example, the effect of area Dt on pressure may be very different for a frozen-in situation or a continuous crushing case. Each failure mode should therefore be treated separately.

L. Gold:

In responding to this question, (El-Tahan, above) a clear distinction must be made between the strength of the ice measured in a testing machine, and the effective strength of the ice given by the total load on a structure divided by area of contact between the ice and the structure. Field data indicate that the effective strength of the ice decreases with increase in contact area, or increase in the width of the structure. For a given structure width or area, however, there is a relatively large range in the values of the effective strength that have been measured or estimated. On the other hand, the true elastic or brittle strength of ice is found to be relatively independent of area, for the size of specimens normally used in strength tests. It is probably reasonable to assume for engineering calculations, an area independent value for the brittle strength of ice. But the number that is usually required for engineering calculations is the effective strength, and this quantity does depend on the area or width of contact.

* * *

O. Vinogradov:

What is the range of collision times for ice floe, structure or ship interaction?

L. Gold:

This question is worded too ambiguously for a direct answer. If by "collision time" is meant the total time of the interaction, then that time will depend on the kinetic energy in the ice or ship, the effective strength of the ice and the relative speed between the ice and the structure or the ship. If by "collision time" is meant the time for the ice to fail when it is subject to impact, that time could range from the order of one-hundredth of a second to many minutes; i.e., imposed strain rates from about 10^{-1} (in the brittle range of behaviour) to more than 10^{-5} (in the ductile range of behaviour).

M. Metge:

Collision times of course depend on the specific geometries of speeds but typically, an ice floe impact at Hans Island lasts between 2 and 10 minutes.

Collision with relatively narrow structures such as drilling platforms can often cause continuous penetration for several hours or days. Individual "events" may last between 5 minutes and an hour.

Ship impacts during ramming for example can last between 5 and 50 seconds.

* * *

R. Frederking:

Failure modes - it would be desirable to develop a failure mode map for full-scale situations: we have this for model scale (i.e. Timco). A map would help define terms, show relations, focus our thinking on processes.

* * *

M. Metge:

I fully agree with the need to develop a "failure map" for large scale interactions. I understand D. Blanchet of Canmar is working on such a map.

One of the difficulties with a large scale "failure map" is that observations are very difficult at full scale. For instance, rubble often tends to hide the failure mode and the observer cannot tell if pure crushing or flaking or cracking is occurring. Mixed modes of failure due to heterogeneities in the ice also cause observational problems.

One possible way to circumvent these difficulties is to characterize the mode of failure by the size of the resulting blocks.

* * *

R. Gill:

Some of your pictures showed the accumulation (or "collar") of ice due to tidal fluctuations around "structures" (e.g. Hans Island). Has any consideration been given to how this ice collar might affect failure modes and the design for ice forces on fixed structures?

M. Metge:

The accumulation of ice around Hans Island and other high Arctic locations has been called an "Ice Foot"; this is somewhat different from an "ice collar" around a pile or pier. The Hans Island "ice foot" can be 100m wide by 20m high and 20m deep.

There has been no analysis of the effect of this ice foot on failure modes. From my observations, it seems that most of the time the irregular face of the ice foot would tend to encourage a mixed mode of failure but sometimes, "pure crushing", "crushing with extrusions" did occur even against the ice foot. There was also a time when the ice foot itself failed and was pushed in by an incoming floe.

* * *

M. Metge:

1. The need to tie in field observations and laboratory tests of various indentation failure modes is clear. The difficulty is that certain phenomena such as crack formation, which can be easily observed in a test tank, are not accessible to the field observer. It is suggested that one parameter which might be common to both field and laboratory observations is the size of the largest blocks as compared to the ice thickness. Failure modes such as pure crushing or flaking or buckling can be easily differentiated using the size of the largest blocks, and that is one parameter that might be relatively easily measured in the field. This concept of the average of the largest blocks is not very different from the concept of "significant wave height" and could be called the "significant

block size".

2. Having been involved with the Hans Island projects from the beginning, I am very aware of the following:

- The scientific possibilities at Hans Island have only been slightly tapped; the untapped potential for observations and measurements is truly great.
- The establishment of a permanent, comfortable camp on the island would make it possible for researchers to initiate projects at a fraction of the cost of previous Hans Island projects, for the benefit of government, industry and science.

* * *

C. Daley:

Concerning the nature of the submergence term, snow is normally associated with friction. Do you think the presence of snow influences friction or submergence?

B. Frederking:

It's a good question. Probably snow influences both friction and submergence. Wetted snow will entrain air, which would increase the effective buoyancy of the ice. This would also have the effect of increasing the friction force; i.e. normal force would be larger. The presence of snow would also tend to increase the coefficient of friction.

* * *

L. Gold:

Can you comment on the relative speed between the ice and structure during pulsation and extrusion?

M. Metge:

Pulsations tend to occur at low drift speeds, in the area of 0.05 to 0.2 knots. Extrusion can occur at any speed from 0.01 to 1 knot or more.

With respect to the vertical speed of the extruded material, it seems to be higher at high drift speeds than during the extrusion phase of the pulsations.

* * *

J. Lever:

Can we address the question of how likely pulsations or ice-induced vibrations are for, say, the Molikpaq?

Are there specific conditions for which pulsations are or are not experienced?

B. Wright:

Firstly, we should discriminate between the terms ice-induced vibrations and pulsations. In my terminology, ice-induced vibrations occurred quite frequently on the Molikpaq in 1985/86 during both non-simultaneous crushing and mixed modal ice failures but resulted in relatively small, local accelerations. By contrast, pulsations occurred only during simultaneous crushing across the entire Molikpaq structure and resulted in relatively large, global accelerations. These pulsations are of most concern in terms of dynamic ice/structure interaction on the Molikpaq and its global effects.

To put this type of pulsating ice crushing interaction into some perspective, the Molikpaq, which was located in the Beaufort's transition zone, experienced crushing failures about 1% of the time over the 1985/86 winter. Other failure modes, stationary ice conditions and open water conditions typified the remainder of the period. Pulsating ice/structure interaction comprised only a small portion of the 1% duration of crushing events and was limited to:

1) Ice thicknesses greater than about 0.5 m.
2) Ice speeds between 0.05 and 0.1 kt.
3) A relatively confined and continuous ice cover.

* * *

N. Allyn:

1. Does the extrusion process produce higher ice loads and pile-up heights than ride-up or ride-down ridge building or pile-up formations?

2. The impact of floes could follow the pressure vs. strain rate curve as follows:

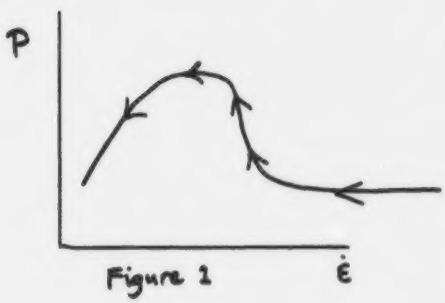


Figure 1

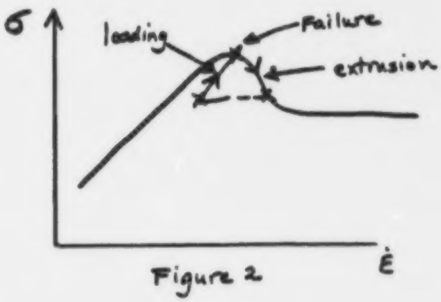


Figure 2

M. Metge

1. The extrusion process seems to produce much higher ice loads but lower pile-up heights than ride-up, ridge building, or pile-up formations.

2. I feel that, during the "crushing with pulsation" process, the strength vs. strain rate curve is involved, but slightly differently than you showed (Figure 1). Part of the process is a straining of the ice and the structure but without failure; therefore it is represented by a point below the curve rather than on it, as in Figure 2.

* * *

L. Gold:

What happens during extrusion or crushing? Are there obvious abrupt failure events followed by a clearing process as indicated by sawtooth load records?

ANSWER:

Yes, each cycle is associated with a little additional extruded material being cleared and the extruded rubble pile grows a little. The ice sheet also penetrates a little more into the rubble, each cycle represents a few centimeters of penetration. It feels like a well behaved smooth process rather than an "abrupt" one.

DESIGN REQUIREMENTS

SESSION 2

Workshop on ICE PROPERTIES

June 21 - 22, 1988
St. John's, Newfoundland

Outline of Presentation by Norman Allyn, P. Eng., of Sandwell Swan Wooster Inc., Vancouver, B.C.

Design Criteria for Ice Loading on Offshore Structures

1. Objectives

The principal objectives are to:

i. Present Methods for Analysis of Sea Ice Interactions with Offshore Structures

ii. Present General Discussion on Design Criteria

- what information is available
- what is used
- what improvements can be made to the data base

2. Ice-Structure Interactions

A range of ice-structure interaction scenarios are encountered in Canada's offshore waters. The different types of interaction considerations are given below:

- Fixed Structures vs. Floaters
  - fixed structures include spray ice/rubble structures, artificial islands, jacket structures, bottom founded monolithic rigs (e.g. Molikpaq, CIDS, SSDC).
  - floating structures include semisubmersibles, ship-shaped vessels, towers, buoys, CDU
- Sloped Sided vs. Vertical Sided
- Glacial Ice vs. Sea Ice
  - glacial ice includes icebergs bergy bits and growlers
  - sea ice includes multi-year floes, ridges and hummock fields, as well as first year ice floes, ridges and rubble fields
- Pack Ice vs. Landfast Ice
- Limit Momentum vs. Limit Stress vs. Limit Driving Force

- Clearing vs. Jamming
- Structure Yielding vs. Ice Crushing
- Steady State vs. Dynamic
- Ride-Up vs. Ice Push vs. Overtopping
- Scour of Seabed (Pipelines)
- Probabilistic vs. Deterministic
- Ice Management
- Load Combinations (e.g. Ice + Earthquake)

3. General Methodology

The ice-structure interaction problem is highly nonlinear, which in general requires a time-step integration of the equations of motion. Where periodic vibrations occur, it has been found useful to perform a frequency domain analysis of the structure alone, ice loading, and ice-structure response.

Mechanical properties of ice are required to determine the ice loads. These properties include:

- temperature
- salinity
- voids
- flexural strength
- crushing strength as a function of strain rate

Probability distributions are required for a number of physical properties:

- diameter
- thickness
- velocity
- orientation
- eccentricity
- ice cover

4. Specific Ice-Structure Interactions

4.1 Ice Forces on Fixed Structures Exposed to Pack Ice

- this can be solved e.g. by using SWIP, a Sandwell Swan Wooster Inc. in-house computer program. Similar programs have been developed by various operators, consultants, and through joint industry studies.

i. floe loads on slope sided structures, upward or downward slopes
ii. ridge loads on slope sided structures
iii. floe indentations into soil berms
iv. floe loads on vertical structure using probabilistic methods (floe class)
v. floe loads on sloped or vertical sided structures using the Monte Carlo approach

4.2 Floating Structures

- Semi submersibles: ICESEMI, 1986 joint industry study, AOGA #309
- Ship-Shaped Vessels: ICESHIP, 1987 joint industry study, AOGA #340

4.3 Scale and Size Effects

- Afanas'ev, 1972
- Ashby, Palmer et al, 1986
- Churcher et al, 1985
- Michel and Toussaint, 1977
- Bohon and Weingarten, 1985
- Sasajima et al, 1981
- Saeki et al, 1979
- Kry, 1978
- EIS curve (pressure vs. aspect ratio), 1982
- Sanderson (pressure vs. area), 1986

4.4 Dynamics

- DYNICE, in-house computer program
- Cook Inlet
- Baltic Sea Lighthouses
- Bohai Gulf

4.5 Rubble Fields and Spray Ice

- ICESIM; developed by Sandwell Swan Wooster in a joint industry study, 1987, AOGA #350
- Mars Island

4.6 Non Linear Analysis

- plastic deformations
- nonlinear finite elements, e.g. ABAQUS
- precise evaluation of local loads is less important
- non linear analysis of hybrid structures

5. Interaction with Scientific Community

- modes of ice failure as observed in field and laboratory conditions
- small and large scale testing
- crystallography and micro-scale theory/testing, including creep and fracture

6. Recommendations

In the above presentation, the following recommendations were made:

- improve on our statistical data base of floe geometries, multi-year ridge lengths, multi-year ridge cross-sections, floe leading edge geometries, and shapes of glacial ice pieces that can impact floating structures

- improve on our knowledge of ice impact properties, such as how ice strengths are affected by varying strain rate

- study clearing/jamming of pack ice through the columns of semisubmersibles at vary speed, diameter, cover, etc.

- define ranges whree pressure vs. area and pressures vs. aspect ratio are applicable

- improve on our understanding of the random nature of ice strength for dynamics

- develop a finite element for ice

Session 2 - Discussion

The following formed part of the discussion period in Session 2.

C. Daley:

How can shorter ridges be stronger than longer ridges?

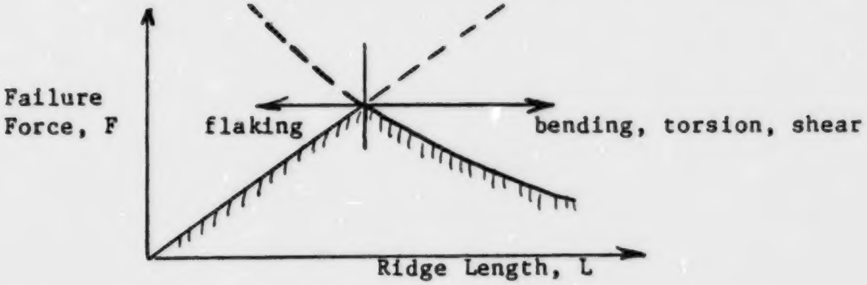
Would the surrounding ice not be weaker than the ridge?

N. Allyn:

Multi-Year Ridge Loads as a Function of Ridge Length

By solving the beam on elastic foundation equations (eg. Hetenyi, M., "Beams on Elastic Foundation", Ann Arbor, University of Michigan Press, 10th printing, 1976), it is apparent that the bending moment in short ridges is lower than for longer ridges with the same cross-section, characteristic length and applied load. This is assuming that the ridge has broken away from the surrounding ice sheet. The stress combination actually incorporates bending, torsion and shear, and a failure criterion is used, so it is not as simple as just reduced moments in short ridges.

Thus up to a point, short ridges are stronger, or fail at a higher applied load. For very short ridges, as I discussed at the workshop, other modes of failure start to govern (eg. flaking) and the loads are reduced again as a function of length. The regions in which these modes govern is shown below:



R. Pilkington:

Do you consider number of floes per year hitting the structure, or km of ice and ridges/km or what?

N. Allyn:

For floes, it is the number impacting the structure per year.

For ridges, we use the number of ridges per kilometer times the number of kilometers of multi-year ice passing the structure per year, to arrive at the design ridge.

REVIEW OF PHYSICAL PROPERTIES OF ICE

SESSION 3

DESIGN ISSUES FOR ICEBERG/STRUCTURE INTERACTION

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Faculty of Engineering/C-CORE
Memorial University

The factors which influence the design of structures for iceberg tolerance depend on the expected interaction scenarios. In very broad terms, large icebergs may impact an offshore structure primarily under the action of steady wind and current forces. Furthermore, the keels of large icebergs may contact seabed structures (such as pipelines and wellheads) installed on bank tops. Small icebergs, on the other hand, may be driven against an offshore structure by wave action. Even for mobile structures intended to avoid iceberg impact, designers must consider both the downtime costs associated with iceberg avoidance and the likelihood of accidental impacts.

To determine the number and type of interactions expected during the lifespan of a structure, we need reliable data on iceberg population, mass and draft distributions, and drift velocities. Because instantaneous velocities govern impact dynamics, we also need to understand wave/iceberg/structure interactions. We need iceberg shape data to predict iceberg motion, stability under towing operations, and contact forces. Contact forces also depend on the material behaviour of iceberg ice during large-scale interactions. Lastly, to estimate downtime costs and the probability of accidental impacts, we need to know the efficiencies of various iceberg detection and deflection systems.

Reasonably good information, or the means to acquire it, already exists on a number of these items. Because rigs log the movement of all iceberg radar targets, iceberg drift velocity statistics are well known. Reasonable knowledge also exists of iceberg mass and draft distributions, as a result of dedicated field programs. Recent laboratory and theoretical studies of wave/iceberg/structure interactions have provided the means to estimate instantaneous impact velocity statistics. Proprietary experiments have established the crushing strength of iceberg ice and its dependence on indentor contact area up to a few square meters. Some knowledge of iceberg management efficiency also exists: water-cannon deflection has proven to be very effective for small icebergs; present iceberg management procedures have succeeded in preventing any serious iceberg contact with drilling vessels.

However, only weak knowledge exists of a number of factors which influence the design of structures for iceberg tolerance. Other than the split and grounding of iceberg "Gladys", no quantitative data are available on the forces generated during large-scale iceberg impact. Is local crushing the only ice failure mechanism likely during an iceberg/structure interaction, or can an iceberg fracture? Similarly, complete iceberg three-dimensional shape data are available for only a few icebergs. Furthermore, the present means to acquire underwater shape data are expensive, error prone, and operationally inefficient. Iceberg scour depth versus return period is also not well known for the Grand Banks. Direct measurement of the required data is difficult, due to the low scour frequency, and lack of detailed understanding of the scour mechanism hampers theoretical methods.

While iceberg population statistics cover many years, detection efficiencies of the systems used are not well established. Actual iceberg populations must exceed measured populations, and this difference likely increases with decreasing iceberg size. Furthermore, to estimate the probability of an accidental iceberg impact, detection efficiencies of the radars used for operational surveillance must be determined as functions of iceberg size and sea state. This is a difficult task.

A major weakness in iceberg management operations is the inability to predict accurately the drift trajectory of an iceberg. This places a greater reliance on deflection. Research has not yet established the level of effort needed to yield accurate drift predictions. A reliable, cost-effective towing scheme for medium and large icebergs also does not yet exist. Thus, in spite of operational experience, designers are reluctant to reduce the iceberg arrival rate in proportion to the success rate of iceberg towing.

Lastly, some factors affecting structural design have received almost no attention. The role of pack ice in driving iceberg/offshore structure and iceberg/seabed interaction is not known. Similarly, the number of repeated iceberg/structure impacts (particularly wave-driven ones) for a given iceberg incursion is unknown at present; yet these statistics directly influence load return-period calculations.

While it may be possible, using existing knowledge, to design a structure for safe operation in iceberg-infested waters, a premium must be paid for lack of knowledge of key factors affecting the design. This premium ultimately influences the economic viability of the development. For many factors at present poorly understood, additional research will undoubtedly prove to be cost-effective in optimizing future designs. One important task for such workshops is to identify which factors warrant the highest research priorities.

DEVELOPMENT OF SATELLITE TRACKED ICE BEACONS TO STUDY ICE DRIFT TRACKS AND OCEANIC HEAT FLUXES OFF LABRADOR

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Physical and Chemical Sciences
Bedford Institute of Oceanography
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Introduction

The sea-ice program of the Bedford Institute of Oceanography is developing satellite-tracked ice-beacons to collect atmospheric, oceanographic and ice data from the drifting pack-ice off the Labrador and Newfoundland coasts. The 5-year program is collecting statistical data on sea-ice drift in response to atmospheric and oceanographic forcing. These data, along with ice drift data from satellite Image Analysis, are used in numerical modelling to determine the reasons for the seasonal variability of the southern extent of the pack-ice. This paper will describe briefly the 1988 winter ice-beacon deployment, followed by a description of a new water-ice beacon that was successfully field tested in landfast ice off the Labrador coast. The program is financially supported under the Panel of Energy Research and Development.

Winter 1988 Deployment

The offshore ice extent off Labrador and Newfoundland in 1988 (Fig. 1) was lower than average throughout the season. In addition, ice thicknesses observed during the ice-beacon deployment off Nain and Makkovik, Labrador were lower than in the previous three years. Only two of the six beacons planned for deployment were deployed during the January field trip, since off Makkovik and inshore off Nain, the ice was too thin to land a helicopter on. Even during the February field trip when another five of six beacons were deployed, the ice conditions at inshore regions were unfavourable to land on. The heavier pack-ice was located offshore over the banks but did not extend as far offshore as the mean conditions (Fig. 1).

The ice-beacons used in 1988 were built by Metocean Ltd. of Dartmouth, N.S. (Fig. 2 and 3) and are capable of providing along with location, real-time atmospheric observations using the ARGOS satellite transmitting link. Four of the ice-beacons deployed collected atmospheric data, while the remaining provided just ice drift rates, derived from their location time series data. The ice-beacons were deployed by helicopter and salinity-temperature profiles were collected.

During the first deployment in late January of 1988, the ice was thin and quickly melted as it drifted southwards. The offshore beacon (solid-dotted track in Fig. 4), was on the ice for only 10 days. It travelled 500 km at a mean rate of 58 cm/sec with higher speeds over the continental slope where the Labrador Current occurs. The inshore beacon, (dashed track Fig. 4) moved slower over the banks at a rate of 20 cm/sec and stayed on the ice for 9 days. The strong ice velocity shear in the offshore direction of 40 cm/sec over 60 km is generally seen between offshore beacons over the slope versus the inshore beacons over the shelf. After dropping off the ice, the ice-beacons became undrogued oceanic drifters. They moved offshore into the Labrador Sea, making cyclonic loops before returning to the shelf regions during persistent onshore winds in the middle of April.

The ice conditions improved for helicopter field work over the banks and outer shelf during the second deployment in late February (Fig. 5). Inshore, the ice was not thick enough to land a helicpoter on. Again the ice-beacons over the outer edge of the bank and the slope quickly moved southwards, generally parallel to the bottom topography at rates of up to 40 cm/sec. They moved around Hamilton Bank inshore onto the shelf (Julian day 70) before moving south towards the Newfoundland coast. The four offshore beacons (Fig. 5) moved in a cohesive unit without much dispersion over the 40 day observation period. This is in contrast to the large shear seen between these offshore beacons and the inshore beacon, which moved southwards at a much slower rate of 15 cm/sec inshore of the banks.

Water-ice Beacon

During the winter of 1988, prototypes of new ice-beacons were field tested in landfast ice, alongside the standard atmospheric ice-beacon off Makkovik, Labrador (Fig. 3). One prototype built by Metocean Ltd. (Fig. 3 and 6) measured the temperature profiles in the ice and surface oceanic layer (Fig. 7). The data was received in real time via the ARGOS satellite system. The beacon deployed on January 24 in 54 cm thick ice monitored ice growth of the landfast ice to 104 cm by the end of April, equal to the 10-year mean for the region.

When the air temperature is much colder than the freezing point of the water (-1.8°C), there is a distinct temperature gradient change in the ice and the homogeneous water condition. The change of temperature gradients in ice and water can be used to obtain the ice accretion rate dh/dt and thus the latent heat flux (Q_l) at the bottom of the ice. The temperature gradient in the ice dT/dz provides the heat flux conducted through the ice (Q_c) from which the oceanic heat flux (Q_{oc}) is obtained by their difference. Following McPhee and Untersteiner (1982) the following equations and constants are used to calculate the latent heat flux Q_l and heat Q_c conducted away from the ice-water interface:

$$Q_l = \delta_i C_i \, dh/dt \tag{1}$$

$$Q_c = (k_o + \beta S/T) \, dT/dz \tag{2}$$

where δ_i and C_i are the density and latent heat coefficient of sea-ice whose product for sea-ice of -4°C temperature and 2 ppt salinity is 2.68×10^8 J/m^3 (64 cal cm^{-3}). The coefficient of heat conduction is also dependent on the salinity and temperature of the sea-ice and can be obtained from the coefficient of freshwater k_0 using the parameter β (117.3 W/m). The coefficient for sea-ice becomes 1.98 W/m C° for the same sea-ice conditions of -4° C and 2 ppt in salinity units.

For the first 2 weeks of deployment the accretion rate of 7.5 cm/week occurred during an observed ice temperature gradient of 10.0°C per 62 cm or 16.2°C/m (Fig. 7). This reduces to a latent heat flux of 33 W/m^2 and conductive heat flux of 32 W/m^2 indicating that the oceanic flux at this inshore location with landfast ice is reduced to near zero. All the water heat content has been removed and no horizontal heat advection occurs in this shallow inland bay. This is contrary to the assumption used by numerical ice models where offshore values of up to 35 W/m^2 for the oceanic heat flux are required to simulate the correct interannual variability of sea-ice (Ikeda *et al.*, 1988).

Conclusion

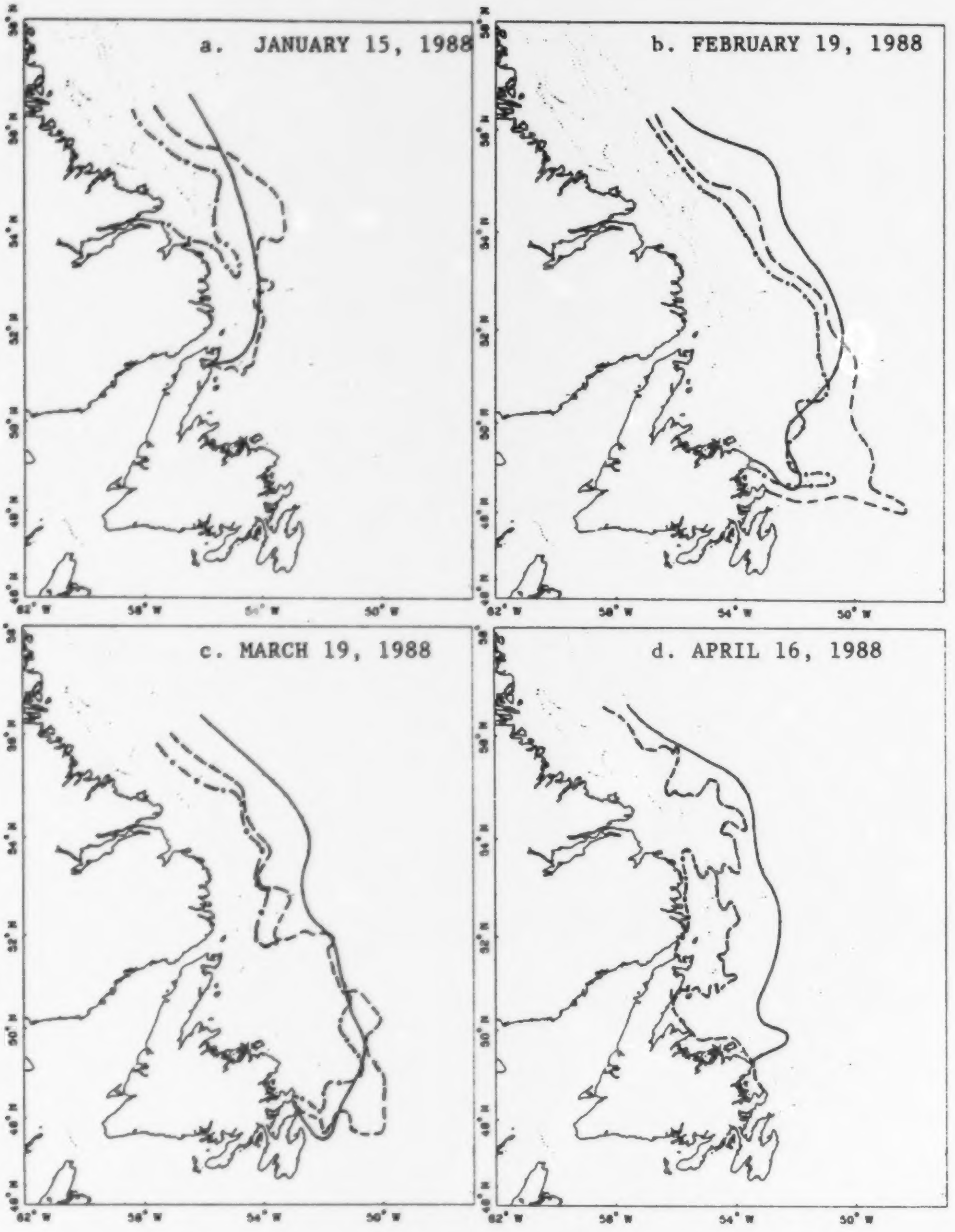
Ice-beacons deployed in 1988 provided reliable ice drift and atmospheric data. Seawards of the banks, they moved cohesively with minor degrees of dispersion. On the other hand, larger ice drift shears exist between those deployed inshore and offshore of the banks.

The development of ice-beacons is providing researchers with data necessary to determine the reasons for the seasonal variability of the southern extent of the sea-ice along the east coast of Canada. With the additional new information on ice thickness from which heat fluxes can be obtained, ice modellers will finally have some idea of the parameters (ice thickness, ice growth and ice decay) necessary for the heat budgets in their numerical ice-ocean coupled models.

References

Ikeda, M., G. Symonds and T. Yao, 1988. Simulated fluctuations in annual Labrador sea-ice cover. Atmosphere-Ocean 26(1): 16-39.

McPhee, M.G. and N. Untersteiner, 1982. Using sea-ice to measure vertical heat flux in the ocean. Journal of Geophysical Research 87 (C3): 2071-2074.


a. JANUARY 15, 1988

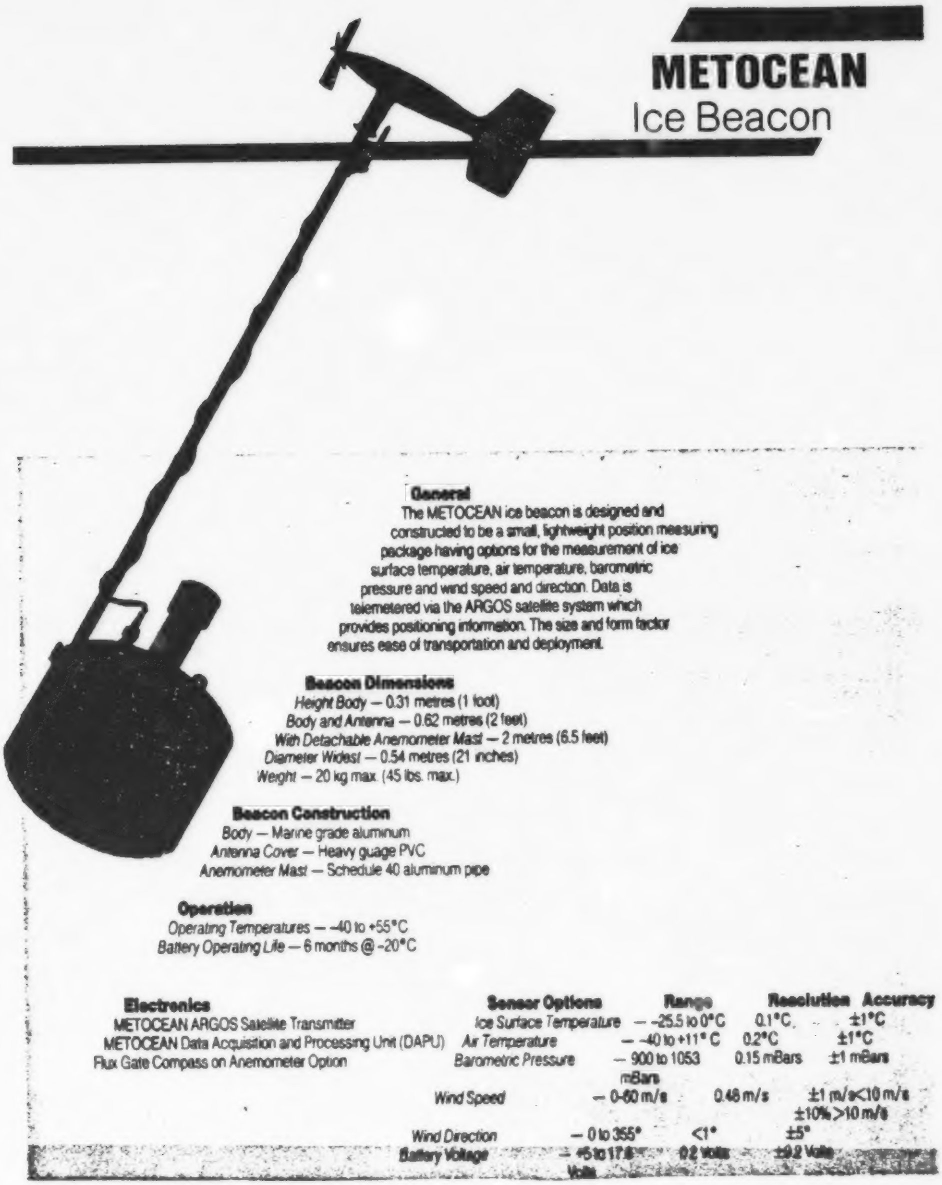
b. FEBRUARY 19, 1988

c. MARCH 19, 1988

d. APRIL 16, 1988

58° N
56° N
54° N
52° N
50° N
48° N
46° N
62° W
58° W
54° W
50° W

Fig. 1. Location of 1988 ice edge (-----) and 9/10 ice concentration boundary (—·—·—) as compared to 10-year mean ice edge location (———) for 1964 to 1973.



METOCEAN
Ice Beacon

General

The METOCEAN ice beacon is designed and constructed to be a small, lightweight position measuring package having options for the measurement of ice surface temperature, air temperature, barometric pressure and wind speed and direction. Data is telemetered via the ARGOS satellite system which provides positioning information. The size and form factor ensures ease of transportation and deployment.

Beacon Dimensions

Height Body — 0.31 metres (1 foot)
Body and Antenna — 0.62 metres (2 feet)
With Detachable Anemometer Mast — 2 metres (6.5 feet)
Diameter Widest — 0.54 metres (21 inches)
Weight — 20 kg max. (45 lbs. max.)

Beacon Construction

Body — Marine grade aluminum
Antenna Cover — Heavy guage PVC
Anemometer Mast — Schedule 40 aluminum pipe

Operation

Operating Temperatures — –40 to +55°C
Battery Operating Life — 6 months @ -20°C

Electronics

METOCEAN ARGOS Satellite Transmitter
METOCEAN Data Acquisition and Processing Unit (DAPU)
Flux Gate Compass on Anemometer Option

Sensor Options	**Range**	**Resolution**	**Accuracy**
Ice Surface Temperature	— -25.5 to 0°C	0.1°C	±1°C
Air Temperature	— -40 to +11° C	0.2°C	±1°C
Barometric Pressure	— 900 to 1053 mBars	0.15 mBars	±1 mBars
Wind Speed	— 0-60 m/s	0.48 m/s	±1 m/s<10 m/s ±10%>10 m/s
Wind Direction	— 0 to 355°	<1°	±5°
Battery Voltage	— +5 to 17.8 Volts	0.2 Volts	±0.2 Volts

Fig. 2. METOCEAN ice beacon used during 1988 ice program.

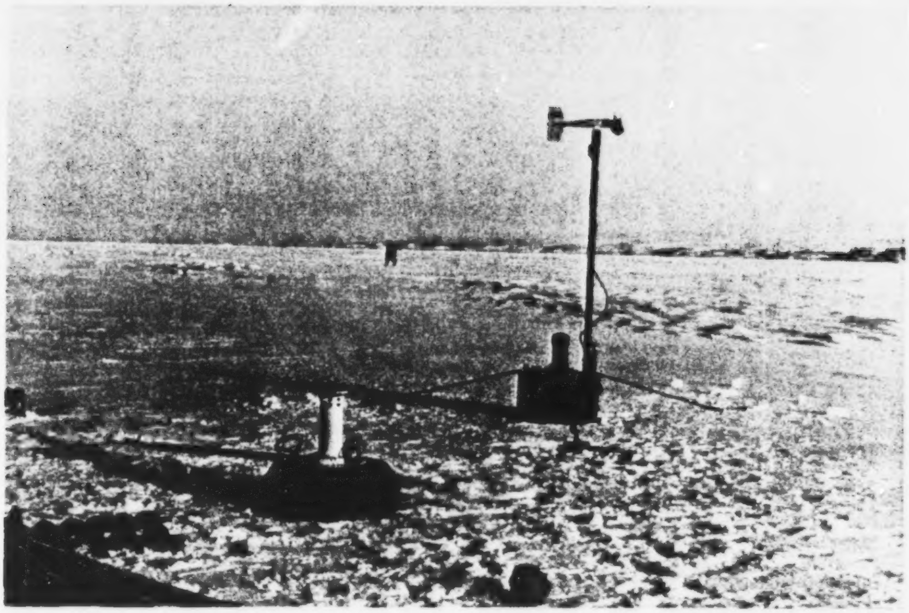
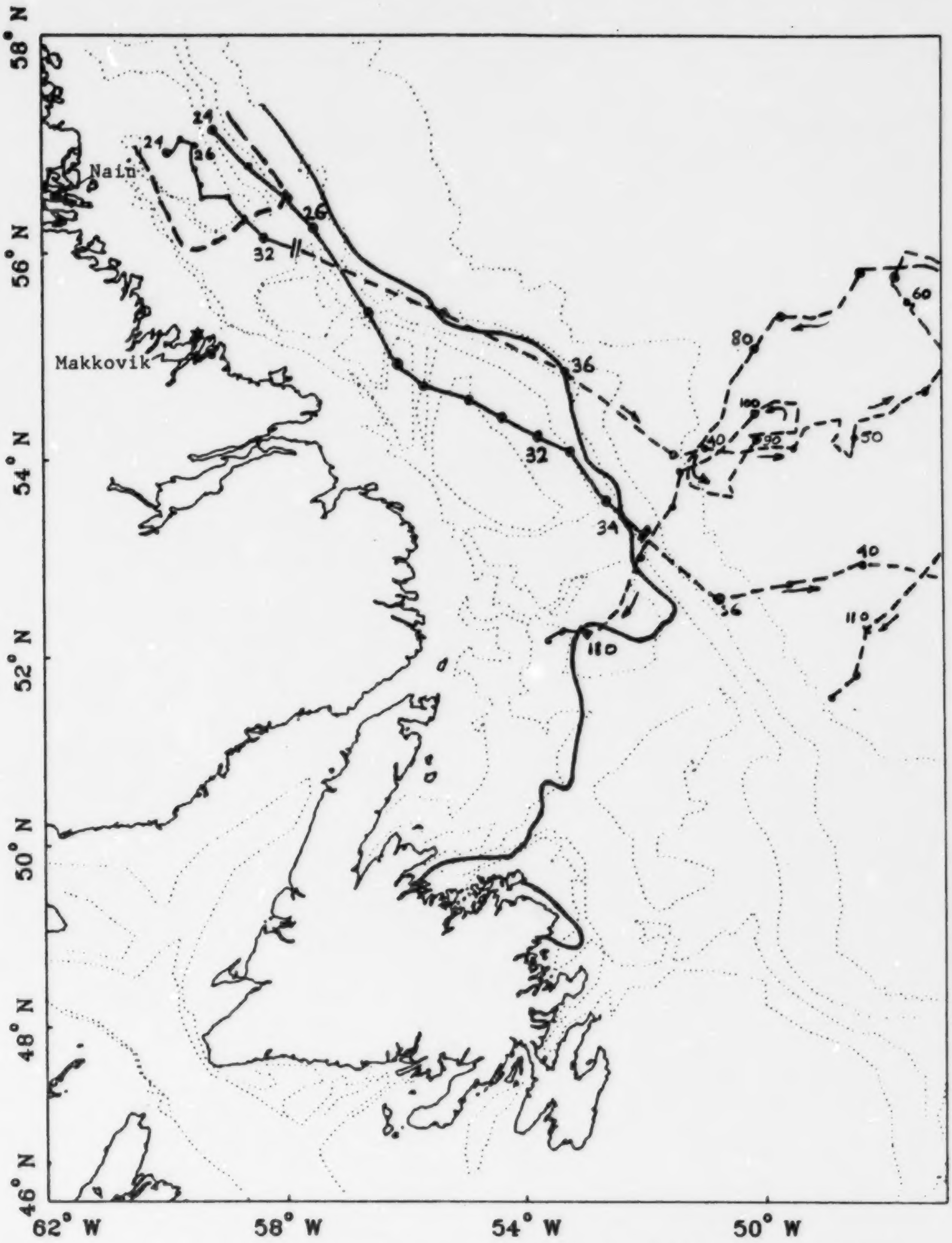


Fig. 3. Ice beacon deployments at landfast ice station on Kaipokok Bay, Makkovik, Labrador, Jan. 24, 1988. Ice beacon, in foreground, collects ice and water temperature profiles (schematic of beacon shown in Fig.6).


58° N
56° N
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48° N
46° N
62° W
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50° W
Nain
Makkovik
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110

Fig. 4. Tracks of ice beacons on ice (solid-dotted lines) and in water (dashed-dotted lines) deployed in January (Fig. 2) with dates along tracks in Julian days. Ice edge (————) and heavy ice area (– – – –) are shown as they occurred during deployment and the location of the landfast ice station is denoted by ✱ off Makkovik.

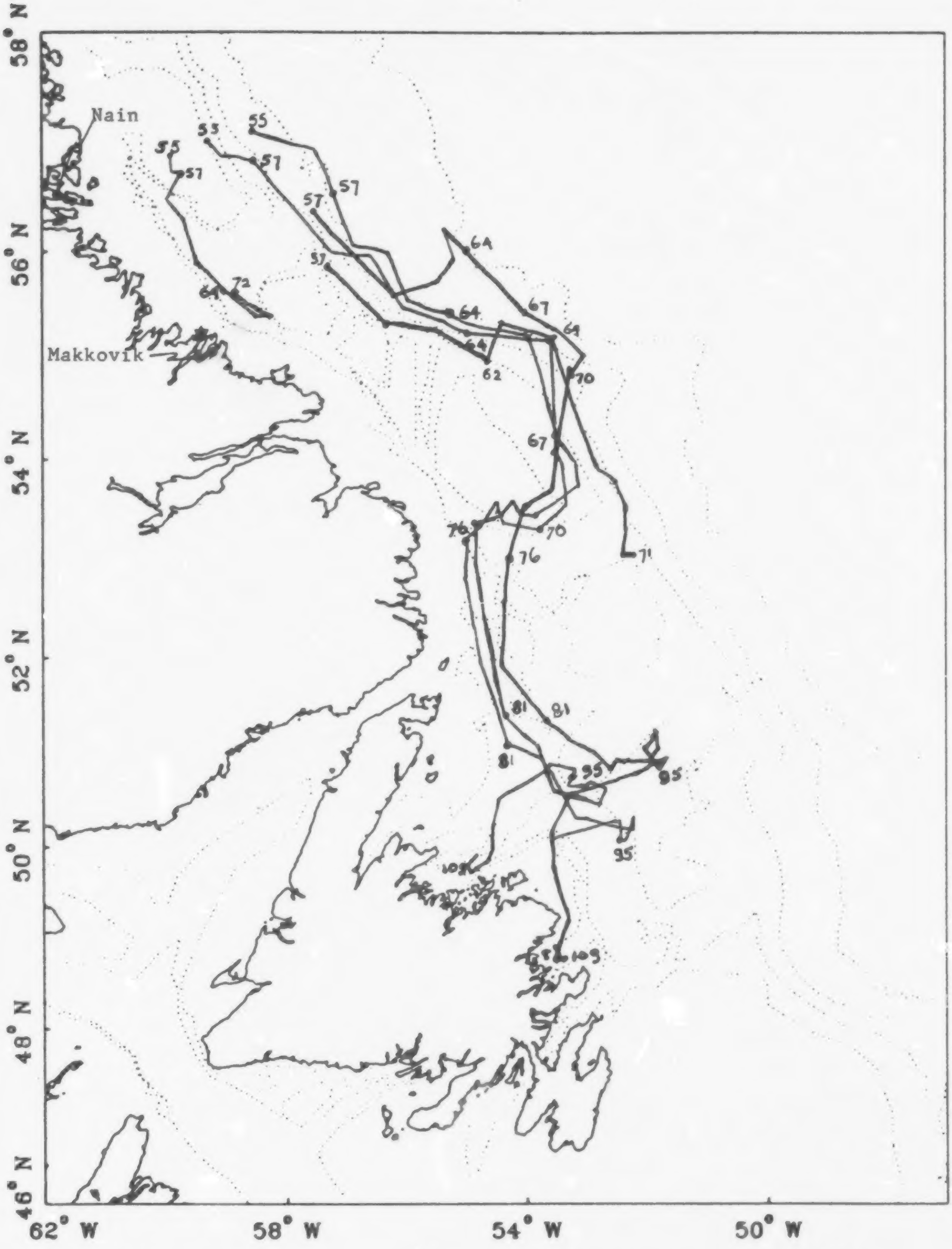
58° N
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Fig. 5. Tracks of ice beacons deployed on February 24 and 26, 1988. Dates along tracks are in Julian days.

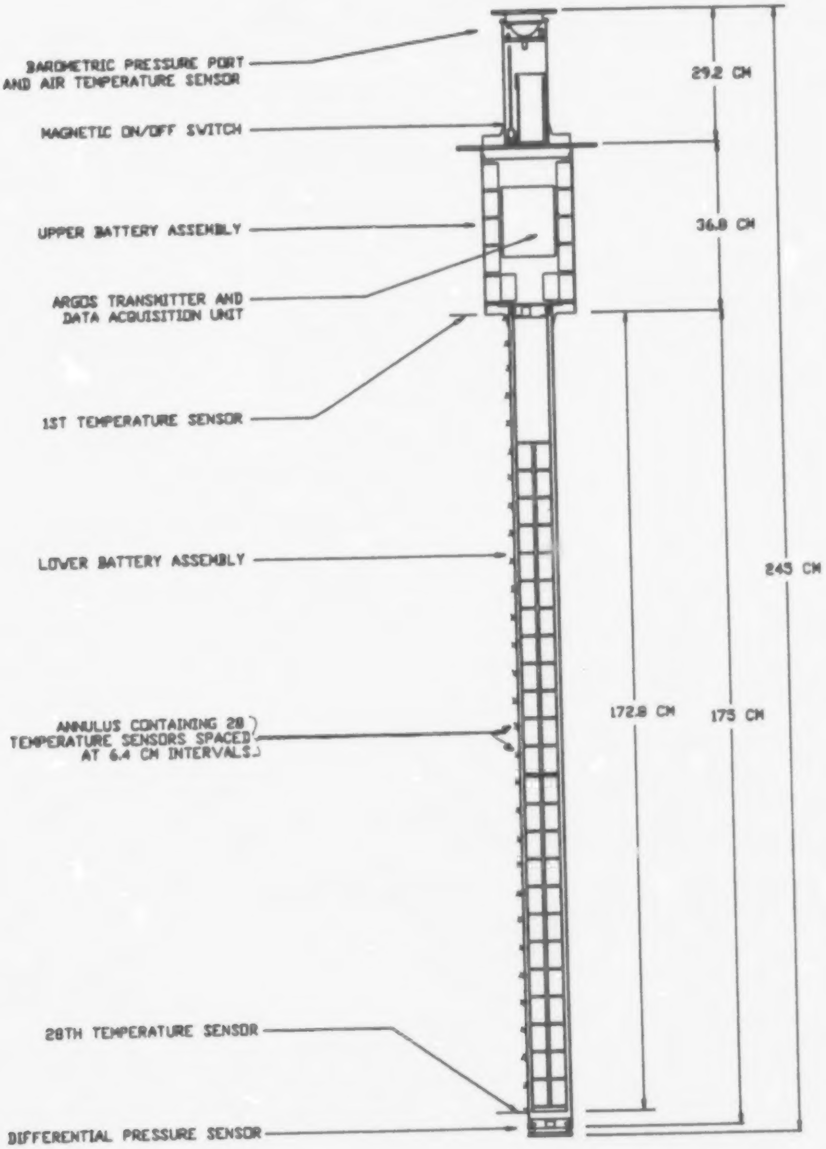
BAROMETRIC PRESSURE PORT AND AIR TEMPERATURE SENSOR
MAGNETIC ON/OFF SWITCH
UPPER BATTERY ASSEMBLY
ARGOS TRANSMITTER AND DATA ACQUISITION UNIT
1ST TEMPERATURE SENSOR
LOWER BATTERY ASSEMBLY
ANNULUS CONTAINING 28 TEMPERATURE SENSORS SPACED AT 6.4 CM INTERVALS
28TH TEMPERATURE SENSOR
DIFFERENTIAL PRESSURE SENSOR
29.2 CM
36.8 CM
245 CM
172.8 CM
175 CM

Fig. 6. Schematic of METOCEAN ICE MONITORING PLATFORM deployed off Makkovik (Fig. 3) in landfast ice. Prototype beacon measures temperatures at 28 locations in the ice and water at 6.4 cm spacing.

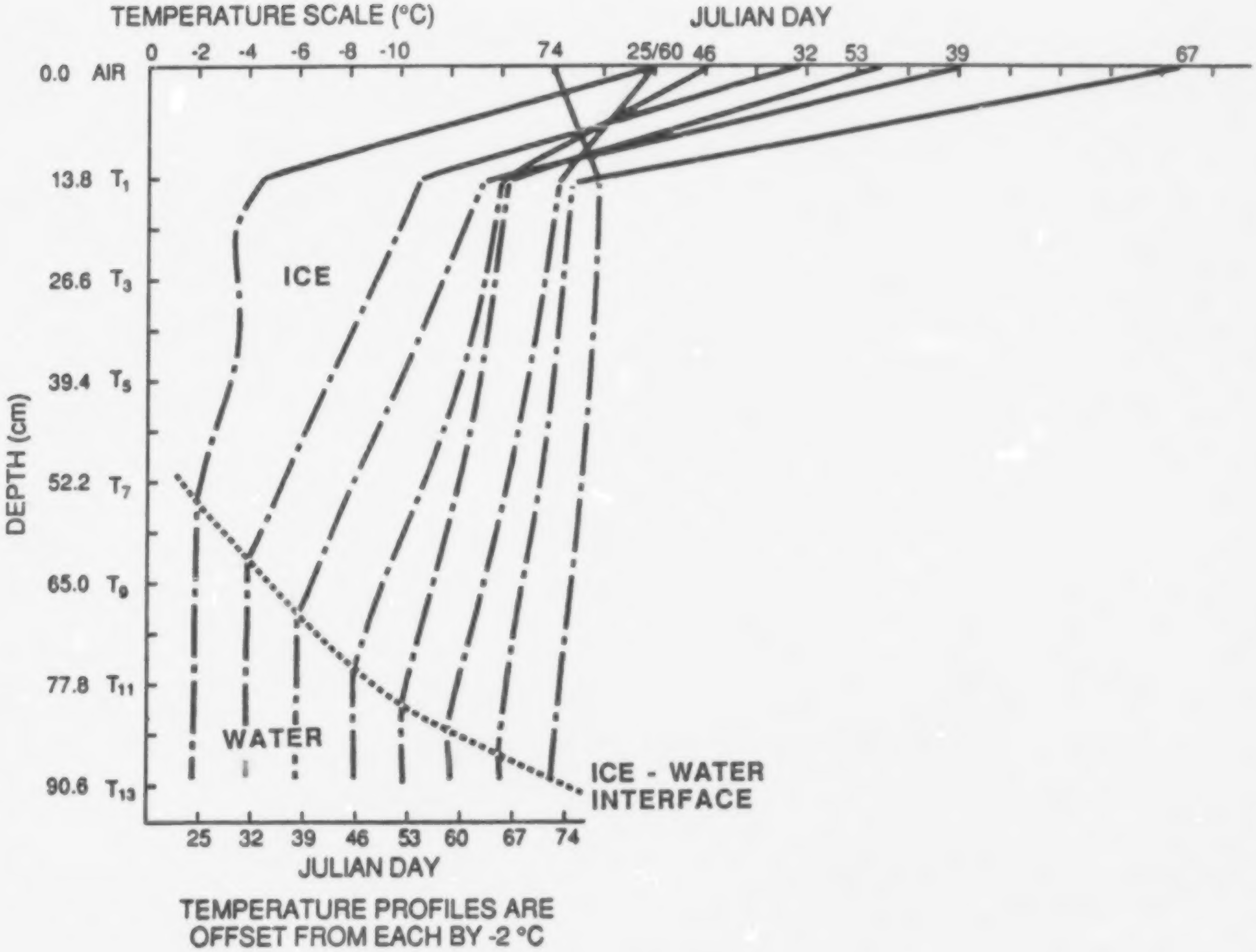

Fig. 7. Ice and water temperature profiles from ice beacon prototype. For clarity each successive weekly profile is offset by 2^{O}C to the right.

An Overview of the Physical Properties of Sea Ice

Summary

W.B. Tucker III

USA CRREL

Hanover, NH

This discussion shall begin with a brief large scale overview then revert to the small scale which is more relevant to engineering design. On the largest scale, there is much variability in the extent of sea ice, both between seasons and between different years. Probably the largest variations occur in the Eastern Arctic, in the Greenland and Barents Seas. About 90% of the ice which exists the Arctic basin each year passes out through Fram Strait. In any given year about 10% of the ice cover in the basin exits through Fram Strait while another 10% melts in place. At any given time, most of the ice in the Arctic basin is multi-year. This is verified by probability density functions derived from submarine topsounder profiles which are often bimodal with a small peak at about 1.0 m indicating first year ice and a larger peak at about 3.0 m indicative of multi-year ice and deformed first year ice. A tail often extending to 20 m or more results from the ridge keels.

Dropping dramatically in scale, an idealized section of first year sea ice has granular ice at the surface, 5 to 15 cm thick, followed by a thin (10 cm) transition zone into columnar ice. The crystals grow larger with depth, their increasing size thought to be a function of the decreasing growth rate. The columnar crystals also have a distinct substructure consisting of platelets on the order of 1 mm across. The brine channels and pockets occur along the boundaries between the platelets which are themselves, fresh ice. The crystal c-axis is oriented normal to the platelet elongation direction, therefore in columnar ice the c-axes are horiztontal and they are often aligned in the same direction. This alignment has been observed to be controlled by the prevailing current at the ice/water interface. The ice salinity has been shown to be proportional to the ice growth rate and these are both inversely proportional to the brine layer spacing. That is, more rapid growth results in closer spacing thus higher salinity. Congelation ice appears to be the predominant textural type in the Arctic. Of many cores studied, only about 30% of the total core length has consisted of granular ice. The granular ice found has either been on the surface as is common when ice growth begins, or associated with deformed ice. We believe that granular ice frequently forms in the voids between blocks in pressure ridges. In sharp contrast with findings in the Arctic, frazil or granular ice makes up about 60-70% of the ice texture observed in the Weddell Sea of Antarctica.

In multi-year ice, the salinity of the upper meter of ice is greatly reduced, often being near zero. Detailed examination of thin sections has revealed retexturing effects in which crystal boundaries have been substantially modified and there is no longer any evidence of the brine layer substructure in the crystals. These retexturing effects are instigated in summer when elevated air temperatures and increased solar radiation substantially warm the upper layers of the ice. While brine volume may be reduced in the upper layers, the porosity and air volume is often quite large, the results of the enlargement of former brine and air pockets during summer. The salinity profile through the remainder of the multi-year ice core is often erratic due to structural changes and boundaries between years, but in general is low, usually not exceeding 4-5 °/₀₀ until the bottom of the core.

Of obvious interest here is the thickness of multi-year ice since the force imposed on a structure is in large part, a function of the ice thickness. We have recently carried out field studies in which we have drilled closely spaced holes (5-10 m) on grids ranging from 50 to several hundred meters long. As might be expected, ice thickness on most floes varies greatly, depending on whether or not the floe contains ridges. However, we have recently seen that most multi-year floes contain evidence of previous deformation. Bottom topography can vary significantly even there is very little evidence of surface relief. There is certainly correlation between topside and bottomside relief, it is only a question of what the correlation is over a given scale. This question is currently being addressed.

Another important engineering concern lies with ridges. Of course there are several types of ridges and the characteristics of each differ. The classic pressure ridge is a linear or zig-zag feature formed by the compression of two ice floes or the closure of a lead. Shear ridges are formed by floes shearing against each other and the resulting ridges tend to be long, linear and have vertical walls consisting of much pulverized ice. Rubble fields consist of many contiguous ridges and contain both shear and pressure ridges. Many drillings and sonar measurements have verified that the keel to sail ratio of first-year ridges is about 4.5:1 while that for multi-year ridges is 3.2:1. Studies of the composition of the blocks in first year pressure ridges indicate a relation between ice thickness and ridge height, implying that there is a limiting height to which ice of a certain thickness ice will build given sufficient force. Using airborne laser profilometers many statistics on the numbers and heights of ridges in various parts of the Arctic have been compiled over the past two decades. The greatest numbers and largest ridges occur off of northern Greenland and along the Canadian Archipelago. These extremely deformed areas result from the trend of the moving ice to compress against and shear along the coastlines. The northern coast of Alaska also has a pronounced shear zone which varies in intensity both season to season and year-to-year. As expected, winter and spring have much more severe ridging than fall and summer. Through such studies one can predict the spatial and temporal recurrence intervals of extreme features.

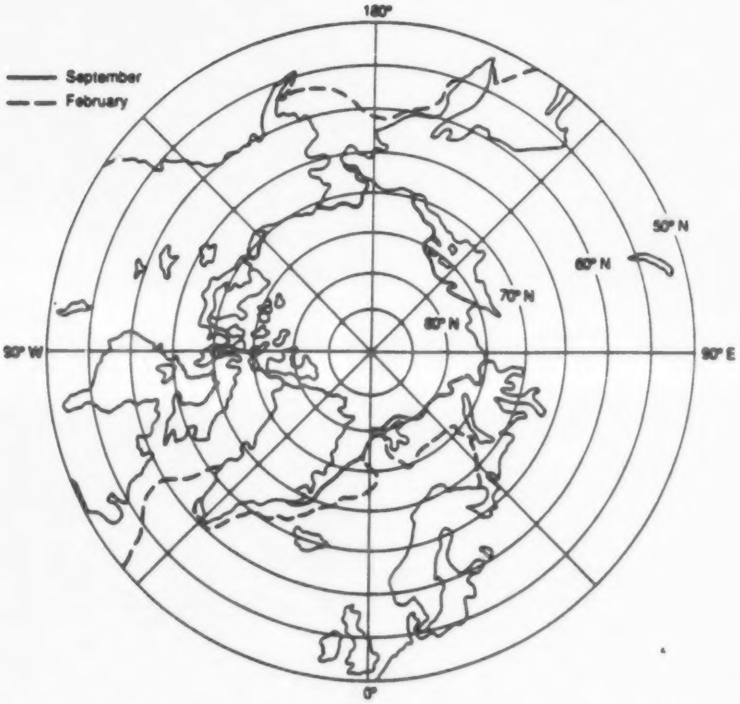
180°
September
February
50° N
60° N
70° N
80° N
90° W
90° E
0°

Figure 1 Mean sea ice extents (concentration exceeding 15%) for the months of February and September averaged for the years 1973-1976. Extents were determined from the Electrically Scanning Microwave Radiometer (ESMR) on the Nimbus 5 satellite (adopted from data presented by Parkinson et al., 1987).

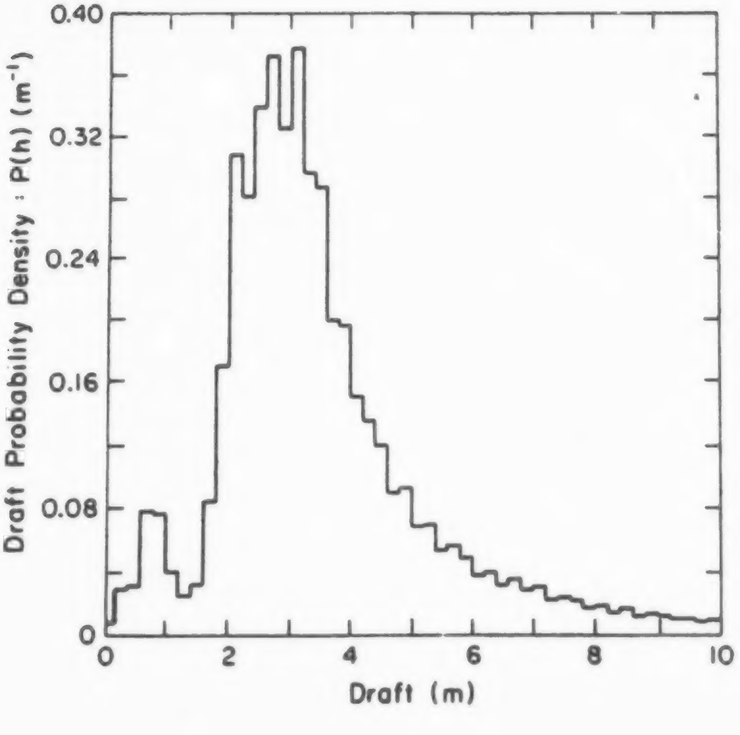

Figure 2 Probability density function of ice draft from 400 km of submarine track in the Beaufort Sea (after Hibler, 1980; data from Wadhams and Horne, 1978).

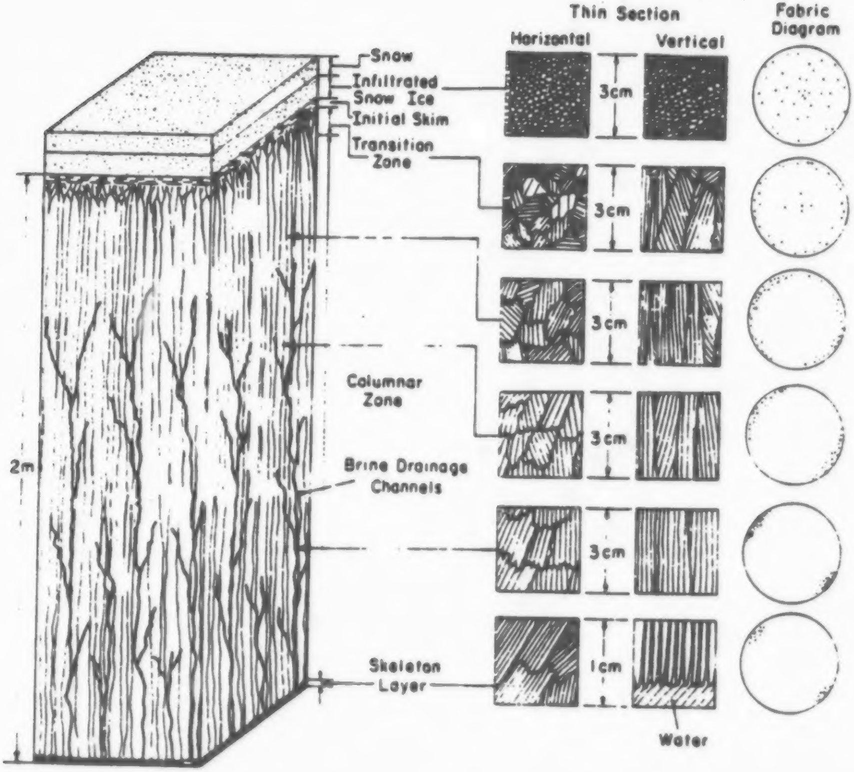
Thin Section
Horizontal
Vertical
Fabric Diagram
Snow
Infiltrated Snow Ice
Initial Skim
Transition Zone
3cm
3cm
3cm
3cm
3cm
1cm
Columnar Zone
Brine Drainage Channels
Skeleton Layer
Water
2m

Figure 3 Schematic depicting major structural and crystal texture and fabric elements in a 2-m-thick first-year sea ice sheet. In this schematic the initial skim of frazil ice is overlain in succession by snow ice and snow. The skeleton layer at the bottom of the sheet corresponds to the region of dendritic ice growth (adapted from Schwarz and Weeks, 1977).

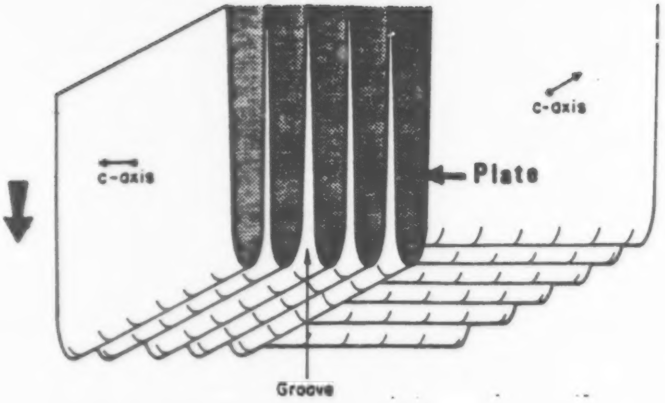

Figure 4 Schematic of dendrite and groove structure of two columnar sea ice crystals. Residual brine is trapped in grooves between dendrites (plates) which remain essentially salt-free. Large vertical arrow indicates direction of ice growth.

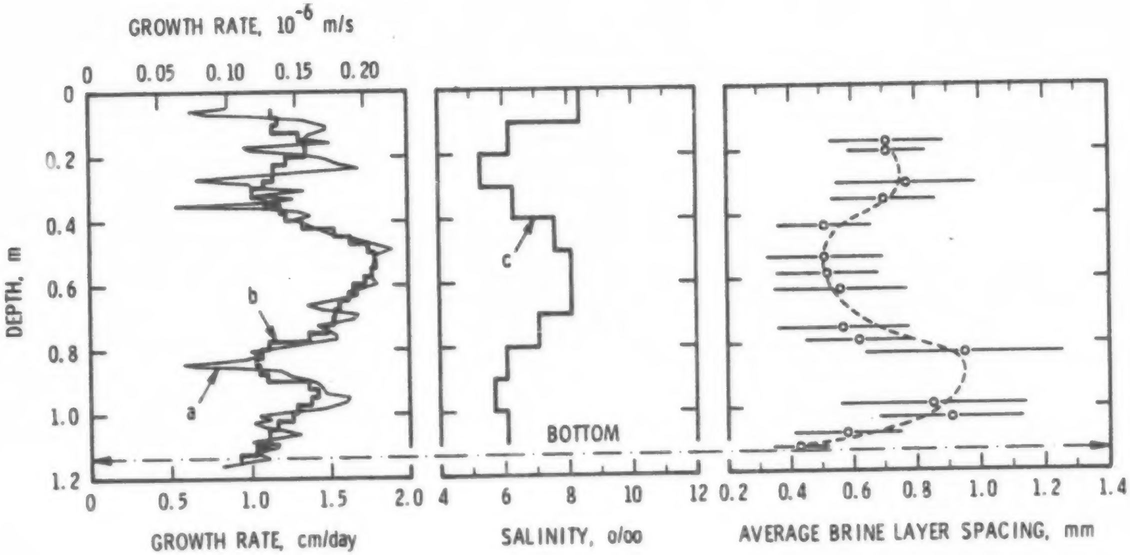

Figure 5 Profiles of growth rate, salinity and brine layer spacing. Curve b represents the mean of calculated growth rate, curve a, for an interval of ±50 mm for every 25 mm (Nakawo and Sinha, 1981).

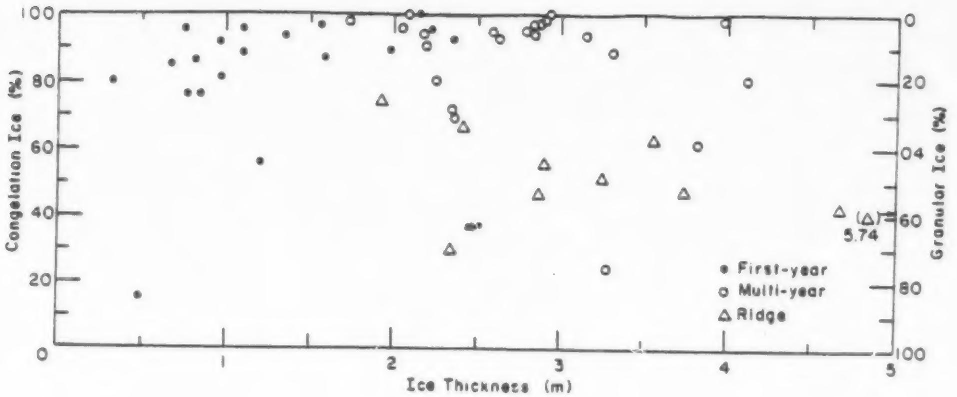

Figure 6 Percentages of columnar and granular ice as a function of thickness for various ice floe types in the Fram Strait. (After Gow et al., 1987b.)

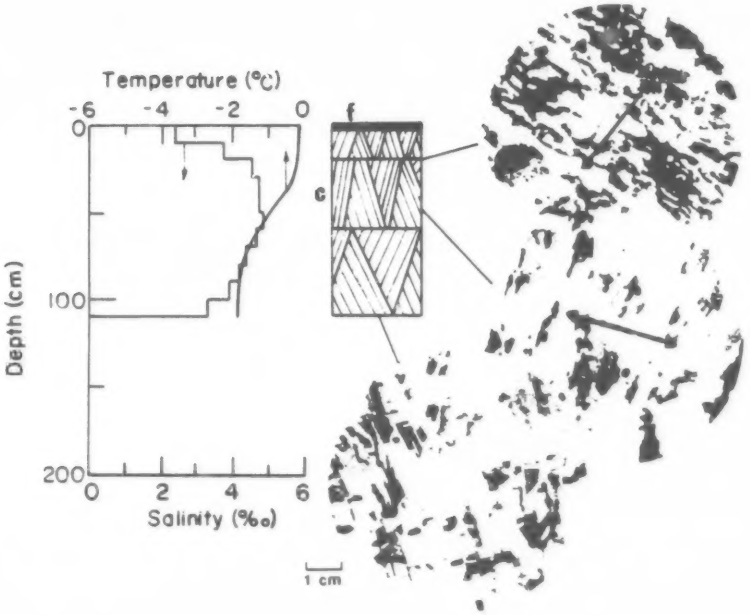

Figure 7. Salinity-temperature-structure profiles of an undeformed first-year floe in the Fram Strait. In the vertical structure diagram the symbols f and c designate fresh water and columnar ice respectively. See text for explanation and discussion. (After Gow et al., 1987b.)

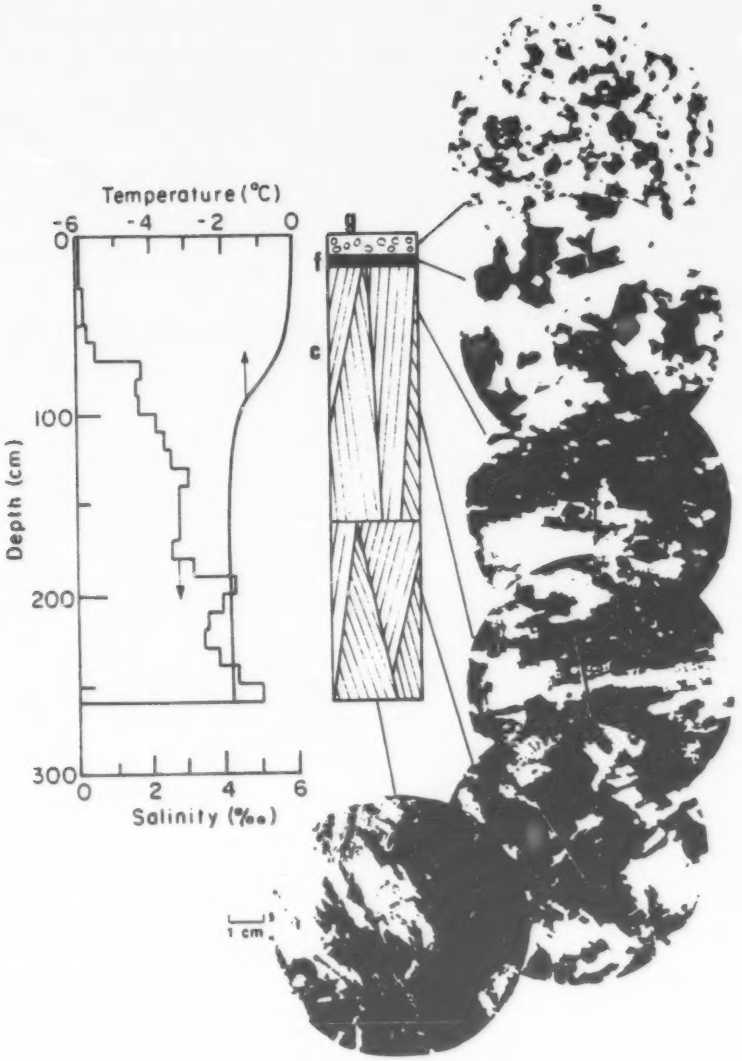

Figure 8. Salinity-temperature-structure profiles from an undeformed multi-year ice floe in Fram Strait. The symbols g, f and c designate granular, fresh water and columnar ice respectively. See text for explanation and discussion. (After Gow et al., 1987b.)

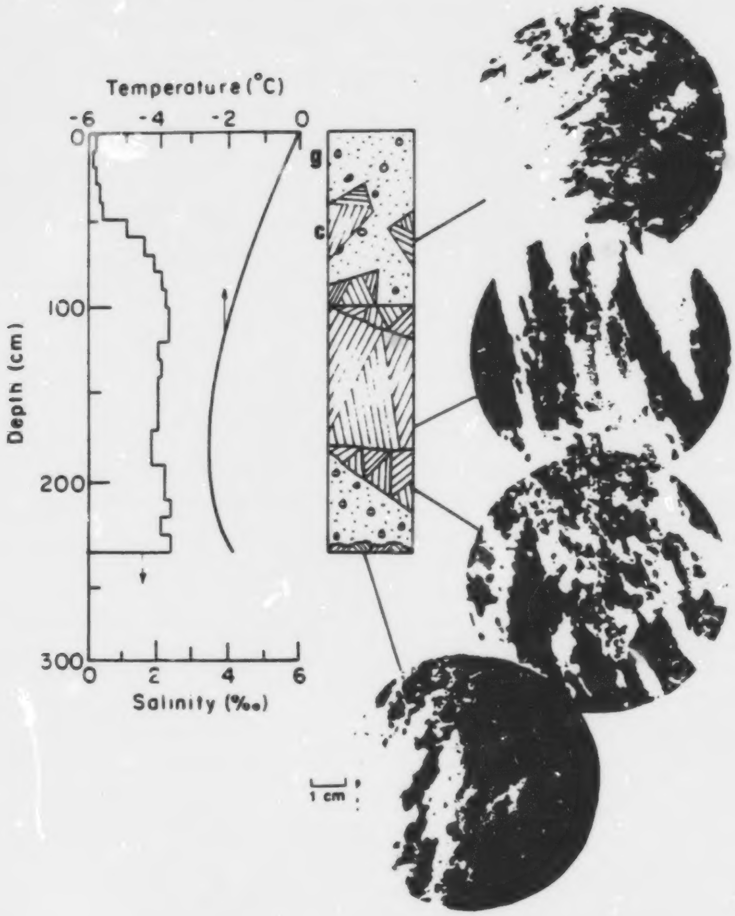

Figure 9 Salinity-temperature-structure profiles through old ridges ice in a multi-year floe in Fram Strait. The symbols g and c designate granular and columnar ice respectively. See text for explanation and discussion. (After Gow et al., 1987b.)

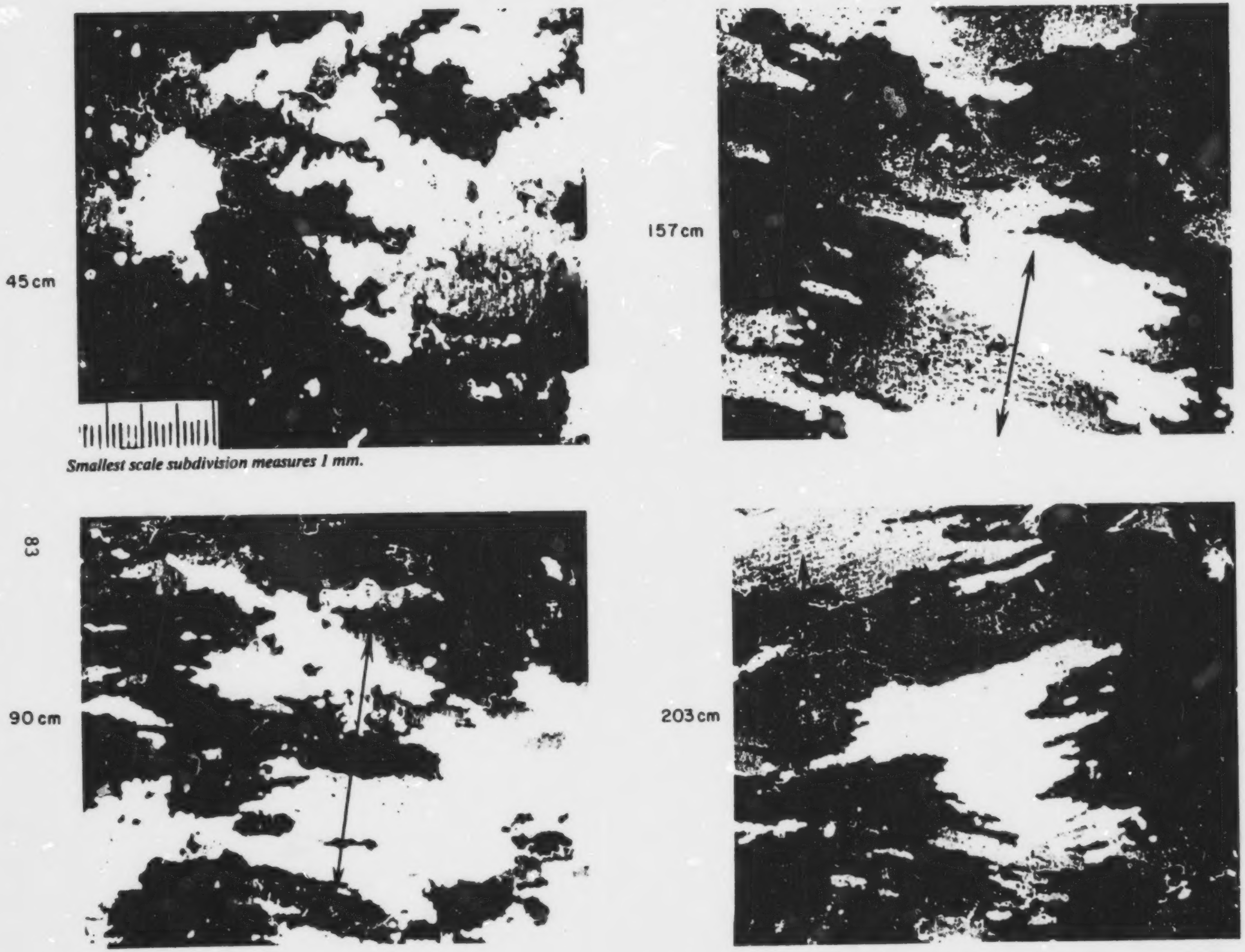
45cm
157cm
Smallest scale subdivision measures 1 mm.
90cm
203cm

Figure 10. Horizontal thin section photographs demonstrating retexturing of ice in the upper layers of an arctic multi-year floe. Note in section from 90 cm that original c-axis alignment (arrowed) is maintained despite nearly complete loss of brine pocket substructures in contrast to substructures preserved in deeper unretextured ice. (After Gow et al., 1987b.)

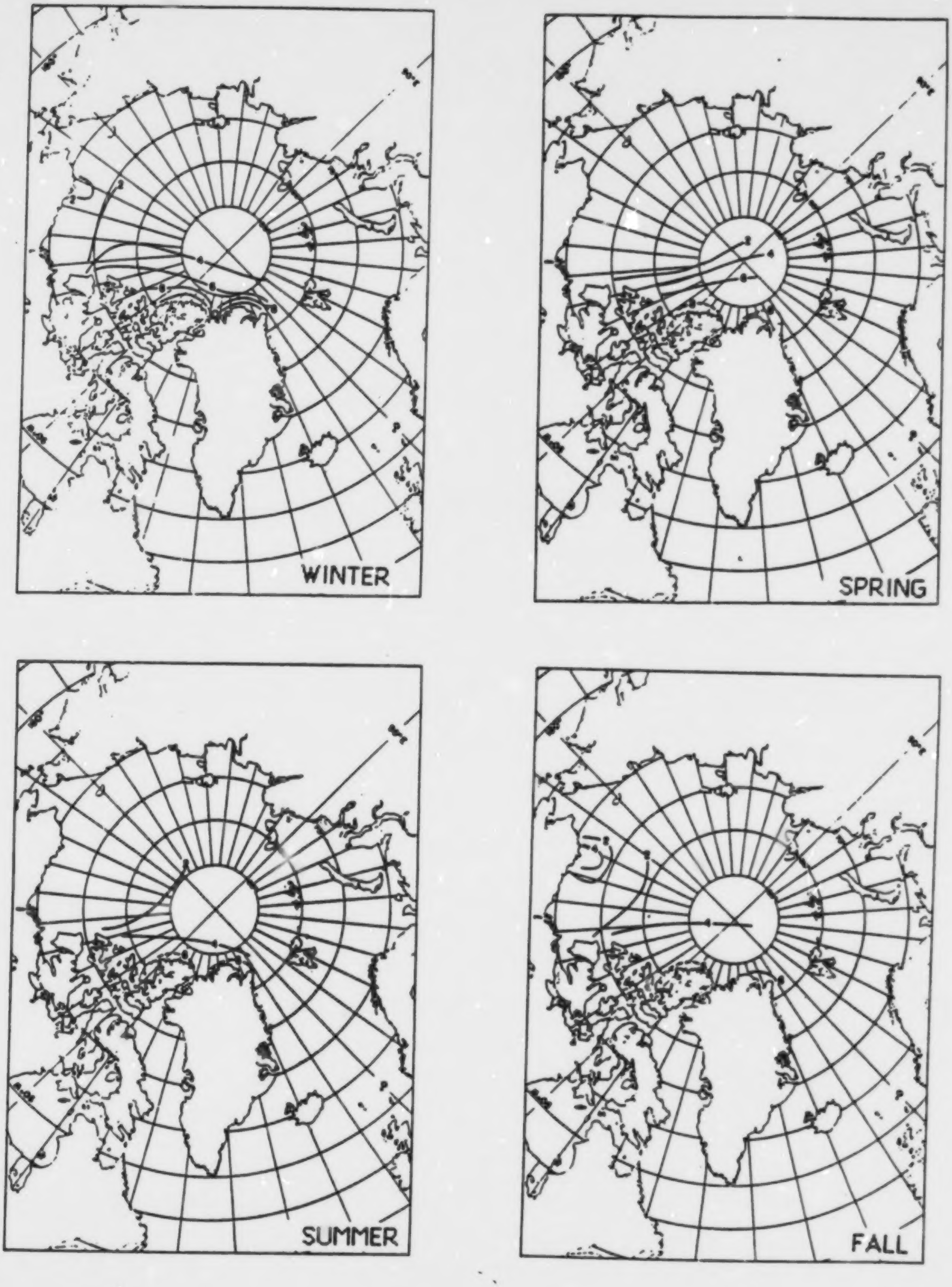
WINTER
SPRING
SUMMER
FALL

Figure 11 Contours of ridge sail frequency (number of ridges per kilometer greater than 1.22 m high) for the four seasons (after Tucker and Westhall, 1973).

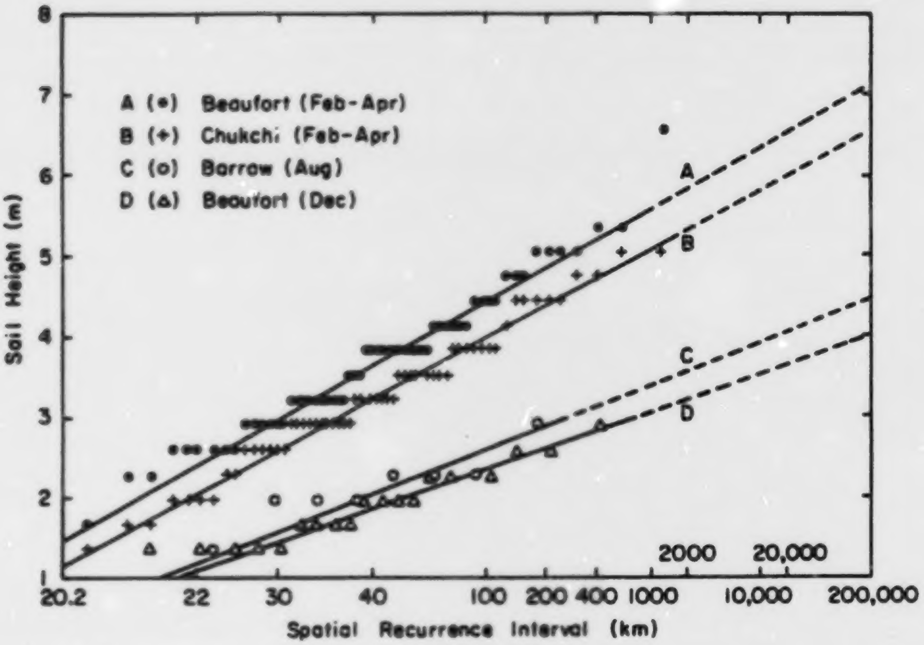

Figure 12. Ridge sail heights versus spatial recurrence intervals.

Session 3 - Discussion

The following questions, answers and comments formed part of the discussion period in Session 3.

R. Pilkington:

I was involved in a ridge keel dive project (in about 1978) and we found a lot of frazil or slush ice alongside the keel of the ridge. I felt it was caused by ice crystals being picked up from the ice bottom and/or frazil formed in open leads being carried along in the current and residing alongside the ridge keel, (like snow on the surface against a snow fence). There is a paper on this in the NRC Workshop on Ridges in Sea Ice which was held in Calgary about 8 years ago.

T. Tucker:

We have also detected frazil accumulations along ridge flanks during our drilling of some ridges. Since we have not seen evidence in our coring investigations of large frazil accumulations in undeformed ice, it is difficult to believe that significant underice generation of frazil occurs in the Arctic in contrast to the Antarctic where frazil is actually a major structural constituent. I agree with your hypothesis that the frazil may be generated in open leads and that which finds its way beneath the ice cover eventually comes to rest against the underside flank of a ridge.

Cores through ridges often find frazil or granular ice. Structural analysis implies that this ice is forming in the voids between the ice blocks. This frazil or granular ice may be precipitated by ice and snow particles generated in the ridging process. A similar process may cause additional frazil formation on the flanks of ridges.

* * *

J.P. Nadreau:

Could the frazil ice that you have identified be highly deformed ice?

The term "Frazil Ice" would be misleading if it is not.

T. Tucker:

We have been using the term frazil ice rather loosely in this discussion. I prefer to use 'granular ice' until one can prove that the ice in question is without doubt frazil. That is, ice particles which have nucleated freely in a slightly supercooled water column. I believe that the granular ice we are finding associated with ridges has components of frazil and pulverized congelation ice associated with the deformation process. The frazil itself may be precipitated by snow and other minute ice particles falling into the water during ridging.

* * *

G. Timco:

In the area of research "needs" which you outlined, I would like to add another one.

We must start thinking about trying to obtain statistics on the flaws (or pre-existing cracks) which exist in sea ice. In particular, we must know the flaw lengths and flaw density. This information is required as input in any model which invokes fracture mechanics. At the present time, we know nothing about flaws in ice.

T. Tucker:

There is information available on multi-year floe flaw distribution nearshore.

Pilkington Review of extreme ice features, held in Calgary, Nov. 1986. NRC Technical Memorandum #141 by Snow & Ice Subcommittee.

* * *

R. Weiss:

I would like to see someone study the failure of floes with measured thickness data - particularly in the bending mode in order to assess the possibility of choosing an equivalent thickness of uniform ice if that is possible.

T. Tucker:

I agree that this would be a very useful study but logistically difficult to carry out. Perhaps thickness studies should be conducted on floes that have failed in bending, leaving enough of the floe intact such that thicknesses could be adequately measured. Similarly, Gary Timco's suggestion that flaws be mapped and subsequently correlated with thickness may be a more realistic method of approaching this problem.

* * *

R. Pilkington:

Are the graphs you showed of sail height vs. ice thickness for grounded or floating ridges?

T. Tucker:

Free floating ridges.

R. Pilkington:

Do you know of any work that has been done on conglomerate floes (i.e. single or multiple floes) behaving as one on impact with a structure?

T. Tucker:

No.

R. Pilkington:

There is a good review of extreme ice features in the NRC Workshop on Extreme Ice Features held in Calgary Nov. '86. NRC Technical Memorandum #141 (?), $20.

* * *

B. Frederking:

What sort of correlation did you find between multi-year floe top-side topography and bottom-side topography?

T. Tucker:

We have examined 6 multi-year floes with grid sizes ranging from 140x140m to 50x450m. Drill hole spacings on these floes ranged from 5 to 10m. The correlation coefficients between topside elevation and bottomside drafts for the individual floes ranged from 0.59 to 0.74. The mean correlation coefficient for the 6 floes was 0.66.

* * *

REVIEW OF MECHANICAL PROPERTIES OF ICE

SESSION 4

SELECTION OF MECHANICAL PROPERTIES FOR DESIGN

L.W. GOLD

Before calling for the contributions to this session, I am going to take a few minutes to present a point of view. I feel it may be useful to keep this view in mind when discussing the information to be presented.

The interaction between ice and structures encompasses a broad range of behaviour. For each behaviour there is a set of mechanical properties that is required for calculations. Ken Croasdale nicely summarized this situation in a table that he presented at a Workshop on the Mechanical Properties of Ice, sponsored by the Snow and Ice Subcommittee in January of 1977.(1) This is still a good statement of the interactions that occur and the mechanical properties associated with them.

Two basic facts must be reconciled when selecting values for the properties. These are the variability that naturally occurs in them; and the need for design specifications to be explicit, even when expressed in probabilistic terms.

The considerable gap that still exists between the requirements of design, and our knowledge of the mechanical properties of ice is apparent in the current draft of the CSA Code for Design, Construction and Installation of Fixed Offshore Structures. Appendix E of that Code is concerned with ice loads, and gives the following three approaches for calculating ice forces (2):

1. Theoretical - incorporating mechanical properties into mechanical models of behaviour;
2. Empirical - taking into account the important variables in the ice-structure interaction, such as structure width and ice feature size and thickness;
3. Experience - the extrapolation from performance measurements to other situations.

In the Appendix it is pointed out that from the first to the last of these approaches there is a decrease in analytical rigour and an increase in confidence in the results.

I suggest that what happens in practise is a combination of the three. Because of the number of factors that affect the properties of ice, and the random variability in some of these factors as well as some of the properties, calculations concerning ice, for both design and operational purposes, will usually have an empirical basis. Theory gives guidance to the form of empirical expressions. Research provides an appreciation of reasonable values of properties to be used in calculations, and of the dependence of the properties on important variables. Performance measurements are the basis for calibration or validation of empirical expressions, and give confidence and justification in their use.

The recommendations in the CSA Bridge Code for the design of piers for dynamic ice forces, is a good example of the empirical approach (3). These recommendations reflect the considerably greater number of performance observations we have for structures less than 5m in width, compared to wide structures, greater than 10m in width. The Bridge Code specifies that for failure of the ice by crushing the force on the pier is to be calculated using the expression:

$$F_c = C_a \sigma_e h w$$

where: F_c is the load on the pier

C_a is a coefficient accounting for the effect of the ratio of the pier width, w, to the ice thickness, h,

$$= \sqrt{1 + \frac{5h}{w}}$$

σ_e is the effective ice strength, the values of which depend on temperature and on the state of deterioration of the ice.

Only four values are given for the effective strength of the ice: 400kPa; 700kPa; 1100kPa and 1500kPa. For these, the state of the ice varies from "substantially disintegrated" due to melting (the low value), to competent ice of average temperature about -2°C to -3°C (the high value). Individuals familiar with the compressive strength of ice, and the factors upon which it depends, will appreciate that the values given for the effective crushing strength are really indexes. They are numbers that take into account the actual probable strength of the ice for the defined conditions, the rate of movement of the ice and the degree of contact between the ice and the pier. The recommended equation for calculating dynamic ice loads is empirical, and its use is justified by field measurements and observations of performance (4).

The empirical approach is being used in the CSA Code for determining ice forces on offshore structures. Equations are being developed, guided by theoretical studies and the measurement of properties in the laboratory and in the field. Ultimately, recommended calculation procedures will be specific and the results of those calculations must be consistent with performance measurements.

The example of the CSA Bridge Code indicates that there is a limit to the degree of variability in a property or a behaviour that can be taken into account in an engineering calculation. This limit may be implicit in the specification, as it is in the CSA Bridge Code, or it may be spelled out explicitly as in the probability based calculations proposed in the CSA Code for Offshore Structures. It is often not required, and may even be impractical, to have the true values of a property for the range of conditions that must be considered in design and operational calculations. As shown by the CSA Bridge Code, what may be appropriate is simply a number, an index. But the number must have the correct dependence on specified conditions, and give a result consistent with experience.

Individuals doing research must accept that although accurate information on the effects of variables is important for understanding ice as a material, the level of importance of this information changes for an operational calculation, and for a design calculation. Table I gives ice properties specified by the CSA Bridge Code and the CSA Code for Offshore Structures. Table II presents variables upon which these properties depend, and an opinion of their significance from the point of view of a design or operational calculations. Tables III and IV present the same information for ice features.

The nature of design calculations is such that only those variables can be considered that affect the design condition. This usually means that some extreme value of a temporal or spatial distribution is used, for example, a thirty year return value. The calculation procedure must be specific. It must give the value of properties or indexes to be used, or state how they are to be determined. Hopefully, the accepted procedure will not be overly conservative.

It is important that committees developing calculation procedures for ice forces, have good information on ice properties and on their dependence on the significant variables. There should be agreed upon, standard methods of measuring, analyzing and reporting these properties and variables. This would ensure a basis for comparing results of different investigations, and a coherent body of data. Having dependable data in a standard format greatly simplifies the task of committees that must decide how a property is to be expressed in a calculation procedure. When we discuss the information on ice properties that is to be presented to us in this session, it would be helpful to have comments from individuals concerned with calculation procedures and with the development of codes and standards on the importance of a particular property from their point of view, of the most appropriate form in which to report values of properties, and on information needs that are not receiving sufficient attention.

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Determination of Ice Loads, 1988, Appendix E. CSA Code for the Design, Construction and Installation of Fixed Offshore Structures, Standard S471 (Draft) Canadian Standards Association.

CSA Bridge Code (56-M-Dec. 1986, Draft) Canadian Standards Association.

Ice Effects on Bridges, 1981, Roads and Transportation Association of Canada.

TABLE I

MECHANICAL PROPERTIES OF ICE REQUIRED

FOR

ENGINEERING CALCULATIONS

STRENGTH:
- compressive
- yield*
- tensile*
- shear*
- flexural
- adhesive

FRACTURE TOUGHNESS*

ELASTIC MODULI*
- Youngs
- shear
- Poisson's ratio

PLASTICITY FACTOR*
(i.e. constants for
constitutive equations)

COEFFICIENT OF FRICTION

COEFFICIENT OF THERMAL EXPANSION*

* not included by Croasdale 1977

TABLE II

VARIABLES AFFECTING ICE PROPERTIES

VARIABLES	LEVEL OF SIGNIFICANCE	
	for design	for operations
Ice		
- structure	low	medium
- grain size	low	medium
- salinity	high regional scale	medium
- porosity	low	medium
- density	low	medium
- flaws	low	medium
Temperature	medium regional/seasonal	medium
Time	high	high
Stress	high	high
Strain	high	high
Specimen size/geometry	low	medium
Method of measurement	low	medium

TABLE III

PROPERTIES REQUIRED FOR ICE FEATURES

Pack Ice, Ridges, Rubble, Floes, Ice Islands, Icebergs

STRENGTHS

- effective
  - crushing
  - flexural
  - shear
    - friction angle
    - cohesion

DRAG COEFFICIENTS

- air
- water

TABLE IV

VARIABLES AFFECTING ICE FEATURE PROPERTIES

VARIABLE	LEVEL OF SIGNIFICANCE	
	for design	for operations
Scale - ice feature/structure	high	high
Type of ice feature	high	high
Source of ice feature	low	medium
Thickness of ice	high	high
Ice concentration	high	high
Surface roughness	medium	medium
Wind velocity (extreme)	high	high
Current velocity (extreme)	high	high
Geography	high	high
Temperature (mean, extreme)	high	medium

A Brief Overview of the Fracture of Ice.

Bruce L. Parsons, Institute for Marine Dynamics
National Research Council of Canada, P.O. Box 12093,
St. John's, Newfoundland, AIB 3T5.

Ice is the most brittle material yet tested, requiring only one joule to create a square metre of crack area. Ice failure observed in the field is clearly due to fracture. The failure of brittle materials is due to a pre-existing population of flaws, that become critical at some applied load. These flaws have both a spatial distribution, and a distribution in size. This may be seen when ice beams, for example, do not break at the point of maximum applied stress. The flaws at this spot may be somewhat smaller, and a larger flaw in a lower stress field may become critical and propagate first. What exactly is a flaw in ice has been hotly debated in the literature. The first person to address the problem, Goetz (1965), stated it was the distance between the brine pockets, parts of a millimetre. Gold (1967) showed that about half the failures of ice are due to flaws already in existence at the time of load application, and the rest are due to dislocation pile-up that accumulates if the load duration is sufficiently long. Recent work by Currier and Schulson (1982), Nixon and Schulson (1986), Sinha (1983) has focused on the possible influence of grains as flaws. Timco and Frederking 1986) showed the importance of the flaw population to overall ice strength. Regardless of precisely which microstructural feature is acting as a flaw in the ice, a statistical distribution is necessary to adequately describe the resulting scatter in measured ice strengths.

Ice failure from fracture is abrupt, there is no creep fracture (sub-critical crack growth) in ice. Ice creeps at any applied load , and if the stress in the ice never exceeds 500 kPa (75 psi), no fracture will be initiated, Sinha (1978, 1979, 1982). Above this stress level the time to fracture initiation has been correlated to delayed elastic strain, due to grain boundary sliding. The effective modulus is reduced by creep to about half it's acoustically obtained value of 10 GPa in ten seconds, and continues to decrease with increased load duration. When cracks are initiated they may run indefinitely or arrest, depending on the loading geometry. Beams break through, but ice under indentation shows crack arrest.

Ice crack velocity is at least 20 m/s (Parsons et al 1987, 1988), and arrests only in certain specific and stable loading geometries, notably indentation. The crack will only increase in length with increased applied load, and it does so in abrupt, discrete jumps. The length of the jumps is not correlated to load rate, or the peak load before propagation, but only to the drop in load. Due to the fracture toughness spatial variability only probabilistic predictions of peak loads and resulting crack length are possible. Despite this there is on average a linear relationship between crack length and applied dead-weight loading, at least for short crack lengths, Parsons et al (1988).

Even for crack velocities greater than 20 m/s, less than 5% beyond the energy of fracture is invested into kinetic energy of the broken ice pieces. The fracture of ice requires such low energy that a mechanism of energy absorption responsible for ninety-nine percent of the energy in an ice-structure interaction has been the subject of recent research. Friction, increase in ice temperature and pressure melting are all available as possible energy sinks. Jordaan (1987) has proposed viscous flow of crushed ice as a possible mechanism, though it is not clear from full scale data what the relative importance of it is, Jefferies (1988). A transition from brittle fracture to plastic flow in small pieces of crushed ice has been proposed by Parsons (1988). No thoroughly convincing experimental evidence is presently available at present, and most likely the energy budget during ice-structure contact will consist of contributions from all these mechanisms. In indentation tests in the field, for example, Nadreau et al (1988) report very wet crushed ice, possibly due to frictional heat and pressure melting.

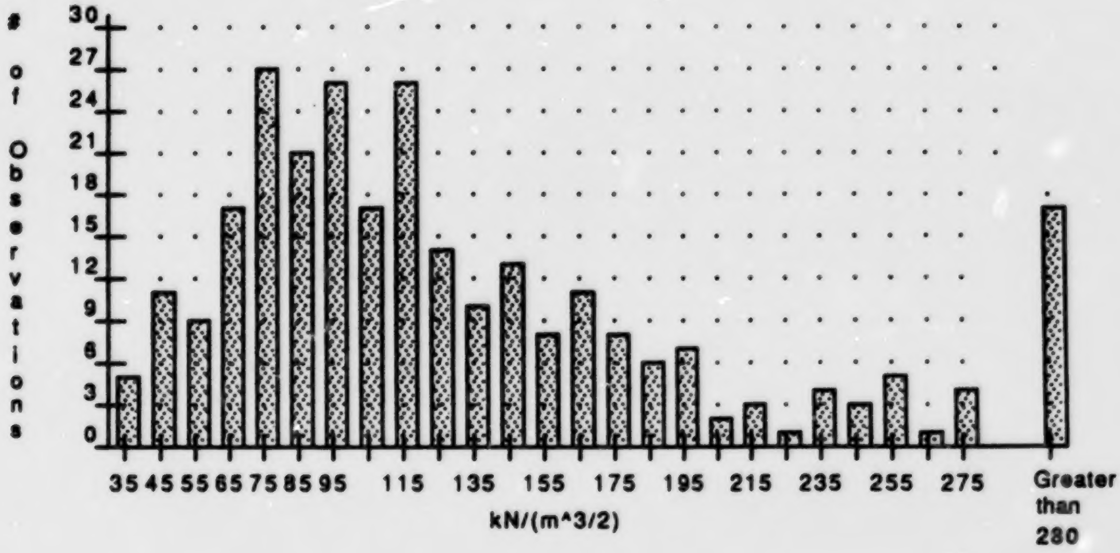
The dependence of ice fracture toughness on temperature, crystal anisotropy and load rate is considerable, and well understood. But the temperature gradients in sea ice cover, and various stress fields developed in the ice mean there will be a significant variability of ice fracture toughness experienced by a structure in ice, and the variation is spatial. The histogram of fracture toughness values from the field show there is a significant tail for high values. These are mostly from cracks oriented across the long columnar grains of cold sea ice, those cracks that would result from spalling of ice in the plane of the ice sheet. The histogram is not meant to imply fracture toughness of ice is not a material property, but to illustrate that the temperature gradients and anisotropy of sea ice will present ice of extreme toughness a significant amount of the time.

A complete methodology employing probabilistic fracture mechanics to predict peak and average loads in ice, with a proper risk analysis, is still under development.

SUMMARY OF FRACTURE-TOUGHNESS DATA FOR FRESH WATER, GLACIER AND SEA ICE

Material	Reference	Test Method	K_{IC} kPa√m	Grain Size mm	Crack Length mm	Remarks
Glacier	Andrews (1985)	Ring	58	9.6	10	Bersaerkerbrae lat 72N, long 24W
	Andrews and others (1984)	SEN bend 3 point	125		18	Roslin Gletscher lat 71, long 24W
Fresh Water	Andrews (1985)	Ring	118	0.91	10	
	Gold (1963)	Thermal shock	50-160	1.5-6	2.4-9	K at arrest of propagation
	Liu & Loop (1972)	CTS	86-471			-46 - -1
	Liu & Miller (1979)	CTS	124	5	50	
	Hamza & Muggeridge (1979)	SEN 3 pt	40-190	8,12	10	Lab grown, three rates, three temp
	Goodman Tabor (1978)	SEN 3 pt	116	1mm to single crystals	10	-13 deg
		pyramid conical	170-290 300		single grain	-20 deg
	Goodman (1980)	SEN 4 pt	118	10	5-10	high load rate 10^3 kPa√m s^{-1}
	Urabe & Yoshitake (1981)	SEN 3 pt	98	5-10	50	-2 deg
	Nixon (1984)	Short rod	87 - 184		-36 - -10,	rate 0.1 -100
	Kusumoto et al (1985)	SEN 3 pt	80-150	single crystal	15	anisotropy
	Timco and Frederking (1982)	SEN 3&4 pt	83	2	12	
	Andrews and Lockington (1983)	Pressurized interface crack	105 clear 50 bubbly	2-5	6.5	

	Parsons and Snellen (1985)	DCB	90-250	10-100	150-250	70N,134W Cold freshwater ice at the mouth of McKenzie River
	Danilenko (1985)	DCB	180 -440 110 -320	∼ 10cm ≤ 1cm	7.5	Large monocrystals
	Nixon & Schulson 1986a,b, 1987	Notched cylinder	67 - 140	≤ 1cm		-50 - -2, rate 0.01 - 10^5
Sea Ice	Urabe et al (1980)	SEN 3 pt	70	3-30	70	Saroma ice,-2 anisotropy wrt c-axis
	Timco and Frederking (1982)	SEN 4 pt	100-140	5-50	12	Beaufort Sea ice -20
	Parsons, Snellen and Hill (1985)	DCB	55-800	10-100	150-250	74N,95W cold sea ice, anisotropy
	Shen, Lin (1986)	SEN 3 pt	60-100 K_{IIc}=70-110	?	64-96	no rate dependence no rate dependence
	Tuhkuri (1987)	SEN 3 pt	136 119		200	Large samples two rates
	Parsons, Snellen Muggeridge (1988)	DT	35-250	10-100	250	initiation and arrest.



Total Field Data on Fracture Toughness of First Year Sea Ice

278 Data Points; Single Edge Notch Specimens, Compact Tension Specimens and Double Torsion Specimens; -2°C to -22°C; Anisotropic Samples Included; Instantaneous (ie Arrest) to 1 Hour Failure Times; 875 kN/(m^3/2) Largest Value, across columnar grains, below -20°C.

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SPECIFIC ENERGY OF IMPACT CRUSHING OF ICE

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Introduction

Similar to other engineering materials, ice has been tested in laboratory and field conditions to measure its strength under appropriate loading. Common methods of testing the ice strength at relatively slow loading or strain rates ($<<1 sec^{-1}$) and the experimental data acquired to date satisfy, to a certain degree, the needs for designing fixed offshore structures acted upon by slowly advancing ice fields. However, for the structures subjected to ice impacts (ships and sometimes fixed offshore structures) the quasi-static strength characteristics can be inappropriate for estimating the ice impact loads. Which of the mechanical properties of ice govern the ice loads, how they can be measured and interpreted in the design practice are the questions addressed in this work.

Experimental Date Base

Three groups of tests have been used for studying the impact crushing strength of ice: drop-weight tests, pendulum impacts and deep penetrating ballistic impacts. The first publication on drop-ball tests should probably be credited to Pounder & Little (1959). They measured the crater diameter and calculated the "impact hardness," which was actually a ratio of the potential energy to the weight of the ice within the crater volume. Drop-cone tests were carried out by Dementyev (1961) with the penetration depths measured. A "dynamic hardness" of ice was then calculated as a ratio of the force to the contact surface area. Perforation tests of laboratory made sea and fresh-water ice slabs were reported by Ross (1969), who used various perforators and studied ice failure modes (no measured test data is reported). Multi-year program of drop-ball tests had been carried out on the fresh-water winter ice cover of Ladoga Lake and reported by Kheisin and his co-workers (1970, 1971, 1973, 1975). They recorded accelerations of the impacting steel sphere and ice cover oscillations during and after the impact, to specify impact variables, such as indentation depth and velocity histories (by integrating the acceleration records), impact duration, an energy recovery coefficient (defined as the rebound velocity coefficient), contact pressure history averaged over the contact plane area, and the specific crushing energy defined as a ratio of irrecoverable impact energy to the ice mass of the crater volume. It was found that the specific crushing energy is almost insensitive to the impact velocity and linearly proportional to the maximum averaged pressures while the recovery coefficient depends on the velocities The Kheisin's testing technique was accepted by Khrapaty and Tsuprick (1976) who calculated the crushing impact energy for sea ice at various ice temperatures A cylindrical indenter with a semi-spherical end was used by Tsurikov & Veselova (1973) for drop-weight test measuring the maximum penetration depth and calculating a "dynamic hardness" of ice as defined by Dementyev.

Pendulum impacts tests have been reported by Glen & Comfort (1983). A flat pendulum hammer was used to crush an apex of a prismatic ice specimen of laboratory saline ice with the impact ice pressure histories recorded from several pressure transducers installed on the pendulum hammer and with the force, mean pressure and contact area histories computed from the transducers' records. The specific crushing energy defined as an energy-to-volume ratio was also computed for different ice temperatures and salinities. When the Glen & Comfort's data are recalculated and the specific crushing energy is plotted versus the kinetic energy, the plot does not reveal a definite dependence but, like in Kheisin's data, rather implies a low sensitivity to the velocity.

A tip shaped as a semi-cylinder situated horizontally was used for the drop-weight tests by El-Tahan et al (1984, 1988). Samples of iceberg ice and laboratory made snow ice were tested with acceleration, penetration depth and pressure histories recorded. Another drop-weight test was reported by Garcia et al (1985) who used a vertical blunt cylinder as the penetrating tip and measured crater's depth, diameter and volume for impact energies ranging within two orders of magnitudes. In addition to the drop-weight tests, the authors presented the results of ballistic tests, thus extending the energy range by one order of magnitudes more. Assuming the impact energy to be identical with the crushing energy makes it possible to plot averaged specific crushing energy versus impact energy for a laboratory polycrystalline ice. A vertical cylinder mounted on a bifilar pendulum was used by Sodhi & Morris (1986) for impacting the vertical face of a floating sheet of laboratory urea ice The data acquisition system recorded the velocity, acceleration, total force and local pressure histories for each ram. Based on the presented data and identifying the impact energy with the crushing energy, the Sodhi & Morris data can be used to plot the specific crushing energy versus impact velocity - no clear tendency is seen. A project including drop-weight tests and large hydraulically driven powerful rams was recently carried out by Mobil at a tunnel excavated within a grounded iceberg. The test records are proprietary, although some data is published (Johnson & Benoit, 1987). Ballistic tests using projectiles dropped from aircrafts on ice cover were orally reported by Rychnovsky (1987, 1988) but not published in the proceeding.

Analytical Model

The above mentioned data cannot be used in design practice unless some impact characteristics of ice are incorporated into an analytical model of ice/structure impact interaction. The format of using the experimental data is to be consistent with the model. Such a model has been developed by Kheisin et al (1975) using the drop-ball tests for studying the physics and mechanics of the impact and for obtaining a mathematical solution. The model was applied for deriving expressions for ice impact loads on a ship side hitting an ice floe (Kurdyumov & Kheisin 1974) and has been later expanded for various applications ranging from drop-weight tests with various indenter's geometries to ramming icebreaking with different bow shapes and to offshore structure/iceberg impacts (Tunik 1984, 1985, 1987). The model is based on idealizing the crushed ice as a visco-plastic medium being dynamically pressed out from the contact zone between moving rigid indenter and the intact solid ice whose boundary retards under the indenter. The extrusion of the pulverized crushed ice mass has been documented in many experimental studies (Kheisin et al 1970, 1971, 1975; Khrapaty & Tsuprick 1986, Glen & Comfort 1983, Johnson & Benoit 1987).

Final expressions for the ice impact load parameters such as the maximum impact force, pressure, depth of penetration and their histories, as well as the impact duration, obtained by Kheisin et al (1975) contain a single combination of the crushed ice viscosity and pressure distribution called a "parameter of dynamic strength of ice" which has an inconvenient and unusual dimension of $N^{5/6}$ sec $^{5/24}/m^{55/24}$. Its values could not be measured directly and had been approximately estimated by recalculating back from measured ice-induced stresses in ship structures. In further applications of Kurdyumov-Kheisin's model to various cases ranging from impact tests to ramming icebreaking (Tunik, 1984, 1985, 1987), the parameter has been used in another form which also has an unusual dimension of $MPa(sec/m^3)^{1/4}$.

These parameters represent the mechanical properties of ice in the ice/structure impact model. They can be calculated from impact tests. However, the physical meaning of either parameter is obscure, while its dimensionality and use are inconvenient. Moreover, almost all of the above mentioned experimental data sources do not contain some details which are essential for calculating their values. These disadvantages can be eliminated by replacing the parameters with the specific impact crushing energy defined as an energy-to-volume ratio. There is a relationship between it and the parameters of dynamic crushing strength of ice used by Khiesin et al and Tunik. For the drop-ball test, the maximum values of pressure in MPa at the center of the contact zone, force in MN, penetration depth in meters and impact duration in seconds can be expressed via the specific crushing impact energy "e" in MPa as follows:

$$P_{max} = 1.23\ e$$
$$F_{max} = 0.97\ (MDe)^{1/2}\ V$$
$$Z_{max} = 1.07\ (M/De)^{1/2}\ V$$
$$T = 0.95\ (M/De)^{1/2}$$

where M, D and V denote mass in MN sec/m², diameter in meters and impact speed in m/s, correspondingly.

Similar equations can be obtained for other indenters and ice/structure impact geometries. A brief summary of the magnitudes of "e", recalculated from the discussed data sources is given in Table 1.

Thus, the specific impact crushing energy "e" represents the mechanical resistance of ice during and immediately after its failure to impact penetration of a spherical indenter. In other words it characterizes a "strength" of ice under impact crushing, while its dimension by definition coincides with the strength dimension. Therefore, this parameter can also be named the "impact crushing strength" of ice - the name used hereafter.

Conclusions

1. The impact crushing strength appears to be an appropriate parameter to characterize the resistance of ice to impacts against engineering structures. Using this parameter in conjunction with the ice/structure impact model enables one to describe properly the physical nature of the impact and to predict the impact ice loads on ships and offshore structures.
2. The impact crushing strength defined as the ice crushing energy per a unit of the crushed ice volume has a simple and convenient dimension of J/m^3 which turns to be identical with the strength unit (Pa). The available experimental data for natural fresh-water and sea ice for a wide range of environmental conditions (from decaying summer saline ice to cold fresh-water laboratory ice) vary approximately from 0.4 to 30MPa, i.e. within two orders of magnitudes at most, which is less than the variation range for a majority of strength characteristics of ice. For particular data sets, the data spread for "e" is typically smaller than for the strength characteristics.
3. The impact crushing strength can be directly obtained from simple tests both in-situ and in laboratory conditions. The testing methods have been designed mainly for studying the ice/structure impact interactions, which typically occurs at impact

velocities ranging approximately within one order of magnitudes from 0.5 to 5 m/s. Such velocities can be achieved using inexpensive simple gravitational (drop-weight and pendulum) testing devices with elevation range not exceeding approximately 1 to 1.5m.

4. The available to date experimental data have been acquired by different researches using different testing techniques and relate to various, and often unspecified, types of ice. Some important details of the testing conditions and results have not always been reported. As a result, appropriate values of the impact crushing strength for particular ice types and conditions can be specified only with a significant level of uncertainty. All available values are summarized in Table 1.

5. The effects of various testing conditions on the impact crushing strength are still mainly unclear. At the impact velocities ranging for 1 from 5m/s, the impact crushing strength appears to be almost velocity-independent, as follows from the data reported by Kheisin et al (1971, 1973), Khrapaty & Tsuprick (1976), Glen & Comfort (1983) and Sodhi & Morris (1986). Some of particular data sets from the two latter sources imply a velocity-dependence. However, a confident conclusion on this matter cannot be made from the data.

6. There is little data to trace the effect of indenter's mass and shape on the impact crushing strength. Kheisin's data of dropping two spheres with different masses (no sphere diameters are reported) in identical conditions imply that the mass effect in not great, if any. An indirect support for this conclusion can perhaps be made from comparing the data by Kheisin et al and Garcia et al. In spite of the differences in the masses and shapes of both indenters, the values of the impact crushing strength obtained from both sources are very close to each other (see Table 1). On the other hand, the Garcia et al data imply a strong reciprocal dependence of the impact crushing strength on the impact energy. Given the energy in Garcia's tests varied within two orders of magnitudes and the velocity varied only from 1.4 to 3.1m/s the energy-dependence may be attributed partly to the mass effect.

7. Data on temperature dependence were reported by Khrapary & Tsuprick for an unspecified sea ice and by Glen & Comfort for laboratory saline ice. Both sources point out to a certain temperature effect but the qualitative estimates of the effect are different.

8. More experimental data is necessary to provide a designer with reliable data of the impact crushing strength of ice for various ice/structure impact scenarios.

TABLE 1

IMPACT CRUSHING STRENGTH OF ICE "e"
(Ratio of impact energy to crushed ice volume)

Ice type and conditions	e, MPa mean (st.dev.) [range]	Test type and data source
Fresh-water ice cover, Ladoga Lake		drop-ball
January -February, t_{air} ~ -50 to -30°C	11.6 (2.6) [5-27]	Kheisin et al
March, t_{air} ~ +2 to +4°C	3.3 (0.8) [2-5]	- " -
Natural iceberg ice		
in-situ, t_{ice} = -6 to -9°C	16.4 (9.9) [2.5-34]	d/b, Johnson & Benoit
laboratory samples, t_{ice} = -5°C	9.4 (2.7) [6.9-15.6]	d/w, El-Tahan et al
Natural sea ice cover		
Can. Arctic, Fox Channel, July	[4.5-6.2]	d/b, Pounder & Little
Kara & Laptevykh Seas	[4.4-26.3]	d/c, Dementyer
North Caspian Sea	[0.4-4.1]	d/w, Tsurikov et al
Antarctic Ice	[1.2-3.7]	- " -
unspecified, t_{ice} ~ -1 to -14°C	[2.2-19.4]	d/b, Kharapaty et al
Artifical snow ice, t_{ice} = -5°C	15.4 (3.3) [9.8-22.1]	d/w, El-Tahan et al
Laboratory polycrystalline ice,-5°C	[1 to 35]	d/w, Garcia et al
Lab. saline ice, -2 to -25°C; S=6; 1 ppt;	[0.4 to 6.0]	p., Glen & Comfort
Laboratory urea ice	[0.12 to 3.3]	p., Sodhi & Morris

Notations: d/b = drop-ball, d/c = drop-cone, d/w = drop-weight, p = pendulum

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INVESTIGATION OF ICE PROPERTIES BY CYCLIC TESTING

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The intention of this presentation is to inform the participants of the workshop about research which is currently conducted at the University of Calgary on mechanical properties of ice.

Relatively little research has been done over the last 20 years on cyclic loading of ice (1-4), although cyclic testing allows to obtain information which can either be used in specific applied problems (ice-structure or ice - ship interaction, interaction of ice fields with water waves, landing of an aircraft on ice, etc.) or provide an insight into the mechanisms of ice behaviour (damping, fatique, inelasticity).

Cyclic tests of ice conducted over some range of frequencies and load amplitudes can be an efficient way of finding visco-elasto-plastic properties of ice since all these properties reveal themselves in a single test. What is needed to successfully accomplish this objective is a flexible mathematical model of ice, a reliable methodology of ice testing, and a procedure for identification of mathematical model parameters based on test results. Research is in progress at the University of Calgary on all aspects of cyclic testing of ice in a uniaxial mode of deformation. As an example, two rheological models of ice which take into account elastic, viscous and inelastic deformations of it at any level of stresses (see Fig. 1) are shown here. In Fig. 1 an element sandwiched between two rigid planes represents the generalized St. Venan friction element which allows to take into account the inelastic properties of ice. This element combined in sequence (Model I) or parallel (Model II) with the Kelvin-Voigt body results in different constitutive equations for ice. The properties of the material in a cyclic loading are represented by a hysteretic loop which describes the stress-strain relationship during one cycle of loading. In Figs. 2 and 3 the nondimensional hysteretic loops are shown for two rheological models given in Fig. 1 for a specific case of model parameters and various frequencies of excitation.

The 4 cm X 4 cm X 40 cm ice specimen will be harmonically loaded using a specially designed and manufactured vibrator having operating speeds from 0 ÷ 100 Hz and a variable magnitude of load. Experimentally obtained hysteretic loops will be used to identify a mathematical model for a given range of test parameters. Note, that inelastic properties are described by only one parameter, q, which simplifies the problem of identification. Two models of ice presented here are only examples of how various properties can be accommodated in one model. Other, more generalized models, can be developed if test results so require.

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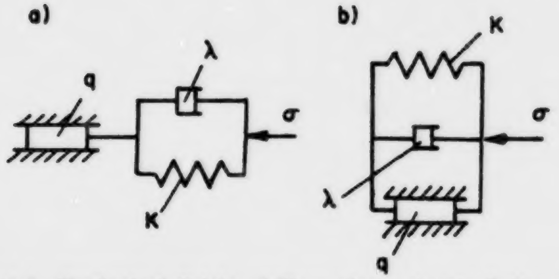

Figure 1 Rheological Models of Visco-elasto-plastic Bodies: a) Model I, b) Model II

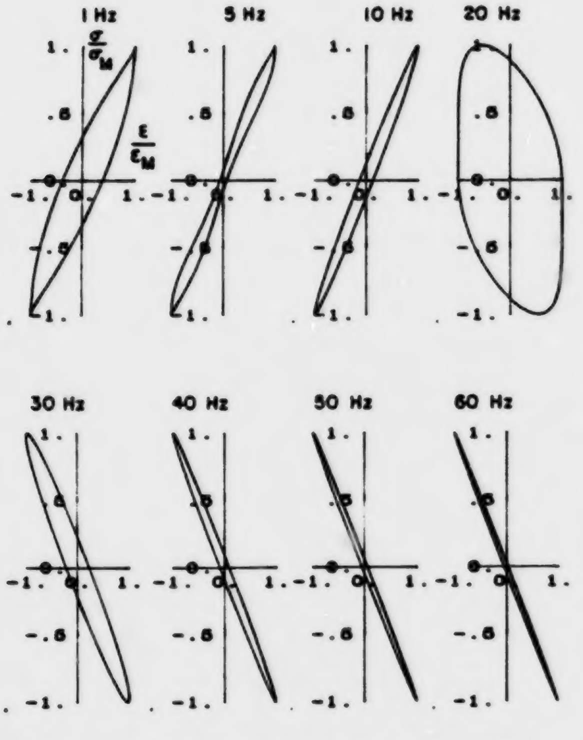

Figure 2 Nondimensional Hysteretic Loops vs Frequency for a Material of Model I ($q = 7.05 \times 10^{-4}$ $1/MPa^2$, $\lambda = 1$ MPa S, $K = 2 \times 10^3$ MPa, $m = 10$ kg, $P_o = 3N$)

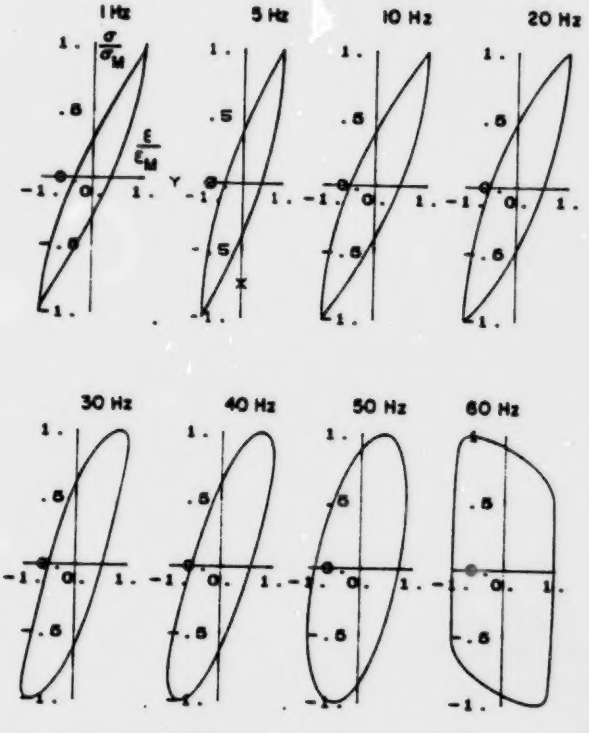

Figure 3 Nondimensional Hysteretic Loops vs Frequency for a Material of model II ($q = 7.05 \times 10^{-4}$ $1/MPa^2$, $\lambda = 1$ MPa S, $K = 2 \times 10^3$ MPa, $m = 10$ kg, $P_o = 3N$)

Session 4 - Discussion

The following formed part of the discussion period in Session 4.

J. Lever:

What is the ultimate objective of fracture mechanics as applied to ice?

Can you outline methodology to relate fracture toughness to load needed to fail ice in a given interaction scenario?

B. Parsons:

At present, yield failure analysis of ice overpredicts the loads experienced by ice breaking structures. Fracture mechanics of ice is being studied in order to account for the data we have at present, and to predict with confidence loads that would be experienced at larger scales.

Up to the present, fracture in ice has been idealized as various simple geometrics with known solutions. These have been unsatisfactory and have overlooked the nature of the contact between the structure and the ice. The first step in understanding this contact is to understand ice hardness, and its influence on crack propagation from a point contact. It is clear as scale increases the effective pressure is reduced from the hardness, and this must be because actual contact area is reduced. This is because of the cracking resulting from each contact creates a rough surface. The next step is to understand how the interaction of cracks from contact points reduces the actual contact area.

The study of rough surfaces is a field of its own (Thomas 1982), and the contact problem has received some research effort already. It has been shown, for example, that the variance of the roughness of a surface increases as the root of the linear dimension of the surface. This clearly indicates why the actual contact area, and thus effective pressure, decreases with scale. While the problems of elastic contact and plastic contact are well understood, the contact between ice and a structure, with its attendant fracture does not clearly fit into either of these. A proper understanding of the fracture of ice beneath a contact, and the scaling of the resulting rough surface is necessary to make predictions of design loads.

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* * *

TESTING METHODS

SESSION 5

Iceberg Field Testing
Medium Scale Iceberg Test Program

J.R. Benoit

The objective of the spherical impact tests performed in 1984 on the iceberg at Pond Inlet was to simulate the impact of icebergs against an offshore structure, and thereby measure the crushing strength of the ice as a function of the contact area.

The test plan was to push several different size spherical indentors into a flat ice surface. A spherical indentor was selected because of its symmetry and similarity to the previously performed dropball tests. In a real iceberg impact the ice may be more spherical and the structure may appear flat. It was estimated that a spherical indentor going into a flat ice wall would give higher stresses than those produced by a flat indentor going into spherical shaped ice because of the relative confining of the broken ice pieces in the former. As it was easier to prepare flat ice surfaces than spherical ice surfaces, spherical indentors were selected as they represent a more conservative condition.

The initial velocity of the spherical indentor was 10 cm/sec with the subsequent velocity decreased to zero following a cosine function of time. This type of velocity profile was selected because it simulates what would occur if an iceberg were to impact an offshore structure. While extreme iceberg velocities are on the order of 150 cm/sec, and average velocities are on the order of 30 cm/sec, the initial velocity value of 10 cm/sec, a low but still realistic value, was dictated by the design of the equipment used.

It was planned to use five different sized spherical indentors such that the final penetration depth was 0.1 of the radius of curvature. The following table shows the final contact area, the final penetration distance, and the radius of curvature for each of the five indentors.

Final Contact Area (m^2)	Penetration (mm)	Radius of Curvature (mm)
.02	20	200
.10	40	400
.50	90	900
1.00	128	1280
3.00	230	2300

Spherical indentors were to be pushed into the flat ice wall by the use of hydraulic rams. The three smaller indentors required only one ram, while the two larger indentors required four rams. It would have been better to use only three rams for the larger indentors, but there was insufficient time to purchase material to build rams larger than the ram used for the smaller indentors. It was therefore decided to duplicate the single ram to obtain the required load.

Since the tests were to be performed relatively fast in order to simulate an iceberg impact, the direct pumping of hydraulic oil to extend the ram could not be used and accumulators were used instead. An accumulator is a high pressure container with compressed gas and oil separated by a piston. As hydraulic oil is slowly pumped into the accumulator the gas on the other side of the piston is compressed gas. During the test a valve is quickly opened and the compressed gas drives the oil into the hydraulic rams which in turn pushes the spherical indentor into the ice at a controlled but rapid rate.

To achieve the desired ram speed, a servo valve controlled the flow of hydraulic oil such that the displacement of the ram followed a sine function of time for 1/4 of a cycle. The corresponding velocity followed a cosine function of time with the initial contact velocity of 10 cm/sec. The 10 cm/sec, while representing a slow iceberg impact, was chosen because of balancing design conditions between the servo valve, ram size, and hydraulic oil operating pressures.

Load cells were placed between the hydraulic rams and the spherical indentor so that the total load could be measured. The vertical weight of the indentor was carried by the ram and not by the load cells. Displacement transducers were used to measure the control motion of the indentor relative to the floor of the tunnel.

Pressure transducers of about 2 cm diameter were mounted at various places on the surface of the indentors to measure local pressures on the indentor. The pressure transducers were designed to be mounted flush with the spherical surface of the indentor, but in fact were recessed. Even so, it is believed that the measured pressures closely represented the actual pressures. The center pressure transducer, however, could not be used as a good indicator of the time of contact.

The tunneling into the iceberg went easier than expected. Compressed air driven chain saws were used for cutting and a small bobcat was used for ice removal from the tunnel. The chain saws created no exhaust problems in the tunnels. The floor of the tunnel was flooded and frozen to provide a smooth level surface. At each test site, the tunnel side walls which became the front and back wall of each test, were made vertical and smooth by means of modified circular saw on a guide.

The first indentor tests performed showed rapidly varying loads and time was spent in determining the cause of this. The feedback control system was optimized to ensure that it was critically damped and the response of the plywood sheets used as shims at the base plate was investigated. After a careful analysis it was concluded that the oscillating loads were due to the breaking of the ice.

In all of the tests, local crushing of the ice occurred in a brittle failure mode. The associated force had an initial frequency near 25 hertz which decreased to 10 hertz. This frequency decrease was apparently caused by the repeated contacting and breaking of the ice at various points on the spherical indentor. This non-uniform failing of the ice caused larger variations in the force, and hence large variations in the nominal pressure.

METHODS FOR SEA ICE IMPACT TESTING

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A1B 3T5

1.0 INTRODUCTION

The present study was undertaken in the Arctic after preliminary tests were conducted in the Institute's coldroom with S2 model ice. The objectives of this study were as follows:

1. to establish the capability of the impact test rig, transducers selected, and other instrumentation at -5°C to -40°C field conditions.
2. to determine the global and local peak loads and rise times in the transient phase of sea ice impact.
3. to examine the nature of brittle failure of sea ice at impact.

A hemispherical impactor was used on specimens of first-year and second year ridged ice. The configurations of edge and surface loading on a standard ice sheet, which have practical importance, were employed. The transducers and instrumentation were chosen to ensure the capture of signals at the instant of highest dynamic load. The design constraints of this experimental study were:

1) maximum impactor drop height of 80 cm.
2) test samples size restricted to a maximum of 80 cm wide, 50 cm high and 80 cm thick.
3) maximum impact velocity of 3.8 m/s.
4) impact load ranging from 25.8 to 220 kg.
5) optimum frequency response of fm data recorder is from dc to 10 khz.

2.0 TEST APPARATUS AND PROCEDURE

The first year ice test specimens were obtained from a trench out on the ice sheet using chain saws and picks. Similarly, the second year test specimens were obtained from a ridge formation. Rectangular specimens about 80 cm wide x 50 cm high and of varying thickness (5 to 25 cm) were prepared using a chain saw. The surfaces were levelled and finished using a spokeshave.

The impactor test apparatus shown in Figure 1 was designed for easy assembly in the field as well as in the cold room. The impact rig consists of a U shaped base frame, a vertical leg support frame, a crosshead member and the drop hammer support frame. The 1.17 m drop hammer was machined from 10.16 cm diameter moulded steel pipe and the surface polished to minimize friction. The hammer drops freely through a 20.32 cm vertical bearing which acts as guide rails. An eccentric lock-release mechanism set on top of the bearing allowed different drop heights to be selected. Different impact loads were obtained by inserting lead weights into the drop hammer. The drop hammer was raised and lowered by a simple cable winch arrangement. The impactor head is a 10.16 cm diameter segment of a sphere with a radius of curvature of 10 cm, screw mounted on a 8.9 cm cylindrical steel chuck.

A piezoelectric force transducer, with natural frequency (fn) of 75 kHz, (max. range 44.48 kN) was carefully fitted between the chuck and the impactor head. A conical steel plug with a contact surface area of 0.712 cm^2 transferred the impact load from the centre of the hemispherical impactor to the transducer. Two small (5 gm) piezoelectric accelerometers (fn = 125 kHz) were fitted with petro wax into cavities on top of the steel chuck. A third shock accelerometer was mounted on top of the drop hammer to measure the overall vibration. A displacement transducer was mounted on the top support frame with its cable attached to the top of the drop hammer.

A schematic of the data recording and acquisition system is shown in Figure 2. The force, acceleration and displacement signals were recorded on a Kyowa RTP-600B data recorder. On playback mode, the voltage drop of the displacement transducer indicated, on the tape counter, the location of events prior to the impact. A Nicolet 4940 digital oscilloscope was set at pre-trigger mode to digitize the analog signals at an effective sampling rate of 50 kHz. About 140 ms of digitized records, representing the transient impact signals, were stored in floppy disks for further processing and analysis.

The test procedure was as follows. In the edge-impact configuration, the ice specimen was supported on its edge and aligned with preferred c-axis in the vertical plane, i.e., impact occurred in the direction perpendicular to the longitudinal axis of the grain. Care was taken to ensure the point of impact was centrally located. The penetration process after impact was observed and photographed. The depth of penetration, the extent of spalling (horizontal and vertical dimensions) and the lengths of significant cracks were measured and recorded. The ambient temperature and the temperature of the ice surface were recorded using a thermistor probe.

3.0 DISCUSSION AND CONCLUSIONS

The test apparatus, instrumentation and data acquisition system proved to be adequate for dynamic tests on ice in the Arctic environment. The data recorder, signal conditioners and power supplies were initially installed in a heated steel box.

The fluctuations of the current load from the power generator and the extreme cold necessitated the use of a heated hut with regular power supplied by the base camp. Hence, the test samples had to be hauled to the test site.

The piezoelectric transducers appropriately measured the transient signals associated with ice impact. An effective sampling rate greater than 20 kHz was necessary to capture the peaks and to minimize errors when digitizing the analog data.

The displacement of the test specimen during impact, the rebound at the base plate and the inherent vibration of the drop hammer accounted for some of the experimental errors in the field.

Further improvements will include higher drop heights to at least 2m and direct sampling of the digital data at a maximum rate of 100 kHz. The ability to make in-situ field measurements and data management and analysis using a microcomputer will be considered for future field tests.

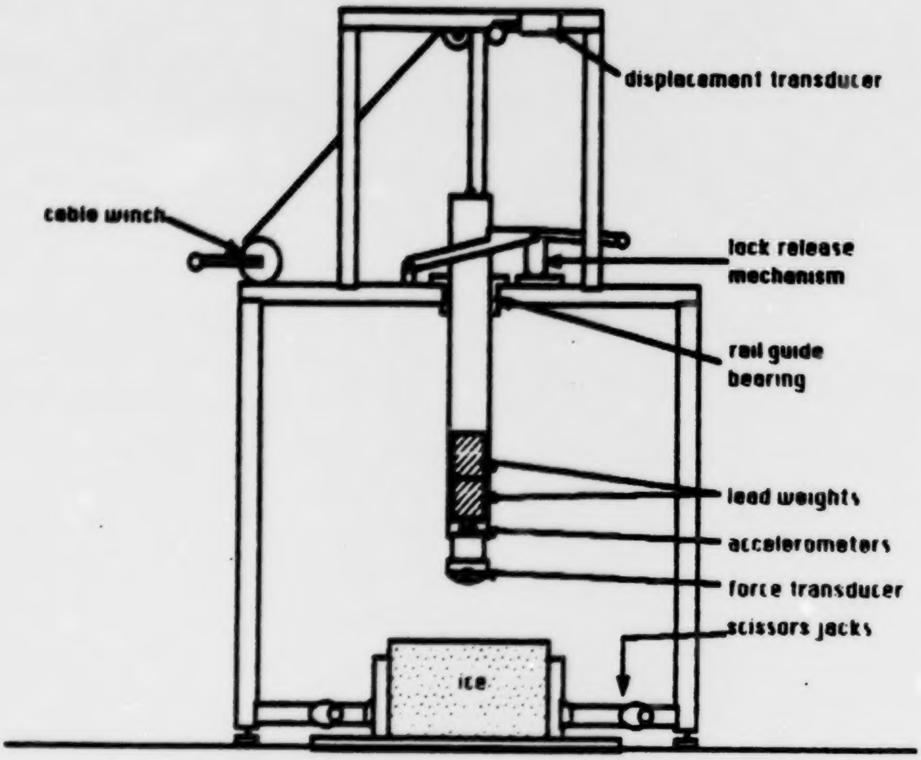
displacement transducer
cable winch
lock release mechanism
rail guide bearing
lead weights
accelerometers
force transducer
scissors jacks
ice

fig. (1) Overall view of impact test rig

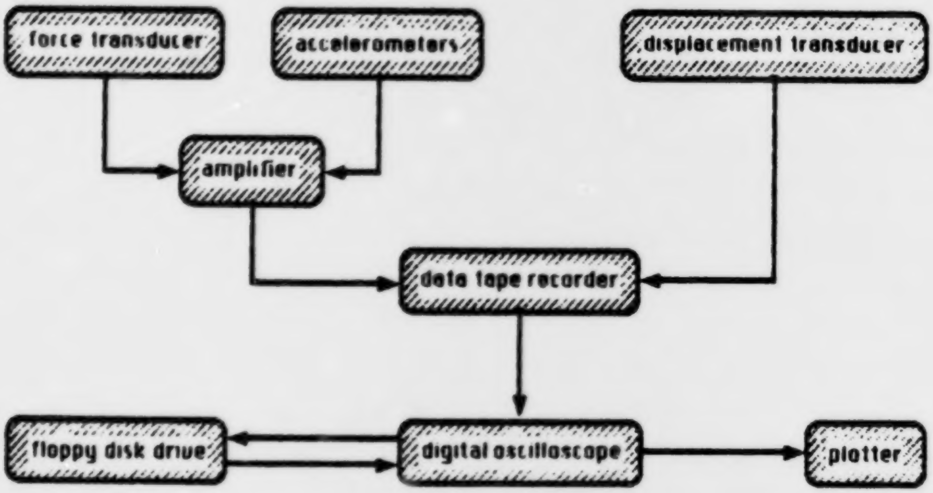
force transducer
accelerometers
displacement transducer
amplifier
data tape recorder
floppy disk drive
digital oscilloscope
plotter

fig. (2) Data aquisition system for ice impact tests

INTRODUCTION TO TESTING METHODS SESSION

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WHY DO WE TEST?

Before considering testing methods it is desirable to briefly review some of the reasons for testing. A primary one is to gain an understanding of the material behaviour of ice so that we have a basis for interpreting what we see in the field. By doing controlled tests on small samples of ice various aspects of its behaviour can be studied.

Testing is done to obtain data on the mechanical properties of ice. These data are used to provide a basis for extrapolating field observations and measurements from one location to another. For example small scale mechanical properties information can be used as a basis for relating large scale ice force measurements made at one location to predicted loads on structures at other locations. Mechanical properties are also a very important factor in physical modeling where they are required for correct scaling. It is necessary to have reliable and comparable methods of measuring mechanical properties in the field and in the model basin. Finally, mechanical properties are a critical input to analytical models of ice loading.

Testing is also done to simulate, at an intermediate scale, actual field loading situations. The Mobil iceberg tests are a recent noteworthy example of this approach. The earlier ESSO "nutcracker" tests are another.

WHAT DO WE TEST?

In considering the ice we test it is helpful to categorize it as being continuous or discontinuous. In almost all loading situations there is a transformation of the ice from a continuous to a discontinuous material. The basic continuum properties which are measured are strength, elastic modulus, fracture toughness, etc. The corresponding physical properties include temperature, salinity, density, porosity, grain structure, etc. Another range of mechanical properties are the interface properties of friction and adhesion. These depend not only on the ice but also the substrate material with which the ice interacts.

In loading ice to failure it disintegrates into a discontinuous material. If it is loaded in compression it is subject to microfracture which eventually leads to a pulverized state or the so called pulverized ice. If it is loaded in flexure it breaks into relatively large pieces. The resulting features are the ridge and rubble fields which are observed in the field. The relevant mechanical properties include cohesion and friction. Related physical properties include feature geometry, particle size and shape, and bulk porosity.

HOW DO WE TEST?

The first step in mechanical properties testing involves sampling. This requires special effort, particularly in the case of sea ice which is subject to brine drainage or iceberg ice which is very fragile. Care must be taken in transporting ice back to the laboratory. Once in the lab the ice must be characterized so that we know what we are dealing with. IAHR (1986) has proposed an ice classification system which has sufficient flexibility to allow the unambiguous description of most ice types likely to be encountered. In addition to grain structure analysis for classification, temperature, salinity and density must be determined.

Another aspect of ice characterization is measurement of naturally occurring ice features such as pressure ridges, hummock fields and grounded rubble piles adjacent to structures or natural obstructions. In these cases the focus is on definition of the geometry of the features and determination of the characteristics of ice making up the feature (block size and shape, porosity, thermal consolidation).

Specimen preparation requires care to ensure that the cross-section is constant and that ends are perpendicular to the axis of the specimen. The ends of the specimen and the loading platens must be flat and smooth to prevent local stress concentrations. Also, friction on the end of the specimen must be controlled to prevent a confined stress condition.

Various loading states may be applied to the specimen. The stress state may be quite simple to make it easier to interpret the results, for example, uniaxial compression. Most actual loading states in nature are complex, involving multiaxial and non-uniform stresses. Therefore other loading states, including uniaxial tension, biaxial compression, triaxial compression, flexure or shear are also used. In each of these cases it is important to know the actual stress state being applied to the specimen. The IAHR Working Group on Testing Methods has prepared a number of reports making recommendations in this regard (see reference list). The preceding has been in regard to testing of continuous specimens. Testing of discontinuous ice is usually done on small scale samples in shear boxes or plane strain compression boxes. Particular care must be taken to ensure that particle size is small in relation to the overall ice sample being tested, and that the stress state being created is the one actually being defined.

Any test must be instrumented to allow quantitative measurement of various test factors. These include load from which stress is determined and deformation from which strain is determined. Other factors which can be measured include accelerations and acoustic emissions. Load measurements are made by means of load transducers and deformations by extensometers or strain gauges. Care must be taken to ensure that these transducers actually measure what it is assumed they are measuring. Response characteristics and sensitivity must be appropriately selected. Finally recorders or loggers with adequate response characteristics must be used.

In any testing it is important that all methods, procedures and techniques be completely and thoroughly documented. Standardization provides an effective shorthand for this. Although standard methods now exist for doing many tests, it is important that such standards not be an impediment to trying new methods. It is very important not to impair advancement, particularly in a field such as ice mechanics, which is still in an early stage of development.

WHERE DO WE TEST?

Testing is normally done in the laboratory which is usually a cold room with temperature control. Ice characterization, specimen preparation and testing are all done in such a facility. Many of the same techniques can be taken to the field and performed in improvised laboratories which depend primarily on the environment for refrigeration. The main advantage in this type of "field" test is that disturbances in transpolation from the field to the lab are greatly reduced.

An alternate approach to field testing is in situ testing which allows the ice to be tested, relatively undisturbed, in its natural state. This is particularly attractive for sea ice where sampling may result in disturbance. In situ testing also opens the possibility of testing large ice features, such as ice islands, at depths for which sampling would be extremely difficult. The bore-hole jack, pressuremeter and flat jack may each be used to measure in situ properties of ice.

The other approach to a field test is the medium scale analogue test which represents an actual field loading situation at a scale approaching the prototype loading situation. In this way it begins to address the question of scale, while at the same time dealing with relatively undisturbed ice. As mentioned earlier, the Mobil indentor tests in an iceberg are one example. In situ cantilever beam tests done to obtain flexural strength of ice covers are another example. Cantilever bean tests relate to ice failing in bending against a structure with an inclined face or an ice breaking ship.

SUMMARY

The purpose of this presentation has been to provide an introduction to test methods for ice by describing some of the aspects and issues of testing. It provides a framework for subsequent presentations and discussions in this session.

REFERENCES

IAHR 1975. Report of Task-Committee on Standardization Testing Methods for Ice, Proceedings 3rd International Symposium on Ice Problems. (Ed.) G. Frankenstein, 18-21 Aug. 1975, Hanover, N.H., pp. 607-618, Nov. 1975.

IAHR 1979. Recommendations on Testing Methods of Ice Properties, Second Report from IAHR Working Group on Standardized Testing Methods in Ice. Bulletin Series A, No. 24, Division of Water Resources Engineering, University of Lulea Sweden, March 1979.

Schwarz, J., et al, 1981. Standardized Testing Methods for Measuring Mechanical Properties of Ice, Cold Regional Science and Technology, Vol. 4, pp. 245-253.

IAHR 1981. Recommendations on Testing Methods of Ice; Third Report of Working Group on Testing Methods in Ice, Proceedings IAHR International Symposium on Ice, Quebec 1981, Vol. II, pp. 938-952.

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LM-AVR-21

METHODS FOR SEA ICE INDENTATION TESTS

J-P. Nadreau, C-CORE; S.N. Chin, NRC/IMD
E. Guy and A. Steel-Fisher, C-CORE

The edge indentation tests carried out at Resolute Bay, N.W.T., in April/May 1988 on first year sea ice incorporated a number of improvements as a result of last year's field experience. These were improvements in the test methods, instrumentation and data management in the -5 to -40°C environment.

The design constraints were as follows:

1. Maximum desired depth of penetration was 15 cm.
2. Continuous indentation rate of up to 1 cm/sec maintaining a maximum resistance load of 260 kN. The latter is the limiting load of measurement system.
3. Ram-actuator displacement was limited to 2.5 cm.

With these constraints and the extreme field conditions, a hydraulic power unit was selected for this series of tests.

1. TEST APPARATUS

The hydraulic power unit consists of a variable axial piston pump with a pressure compensated load sensing device. The hydraulic pump was driven by a 8 hp, 4 cycle gasoline engine which was electrically started. The line pilot-operated pressure relief valve maintained a designed pressure of 13.8 MPa. The entire hydraulic power unit with its circuit components weighed about 1.5 tonne.

The ram-actuator unit as shown in Figure 1 consists of a single acting hydraulic actuator mounted on a base frame with attached skis. Four screwjacks with 12 cm. steel, circular-shaped plates were mounted on one side to distribute the resistance load evenly during indentation. A load cell was screw mounted on the actuator shaft which terminated with the rigidly attached indentor head. Displacement transducers were mounted on the ram-actuator frame to measure the depth of penetration and the axial distortion during indentation. Flexible hydraulic hoses with drive couplings were used for the extension and retraction of the actuator.

Two indentor head geometries were used: hemispherical and flat cylindrical. For the hemispherical head, three test configurations were incorporated, namely: a) smooth polished surface, b) knurled surface with spiral grooves radiating from the pole, c) molded, in which the smooth indentor head was heated and melted into the ice wall. The diameters of indentor heads were 2.8, 3.9, 5.5, and 8.0 cm which gave an incremental surface area of approximately twice the preceeding diameter.

2. INSTRUMENTATION AND DATA ACQUISITION

A schematic of the instrumentation and data acquisition is given in Figure 2. A 20 cm stroke (rectilinear potentiometer 0.04008 mm/mV) displacement transducer was used to measure the displacement of the indentor head with respect to the frame as the indentor penetrated the prepared ice wall. Two spring loaded 5 cm stroke potentiometers (0.01008 mm/mv) were attached at opposite ends of the actuator frame with the tip in contact with the ice wall at the beginning of the test; their purpose was to determine the axial distortion during indentation.

A tension/compression load cell (max. load 245 kN, 9.433 kN/mV) was used to measure the load during indentation. The acceleration at indentation was measured using a quartz shock accelerator which had full scale range of 100 g. The output of this transducer was 50.2 mV/g with a resolution of 0.001 g and a resonant frequency fo 33.5 kHz. The accelerometer is a constant voltage piezoelectric sensor with its own 27 V dc power supply. Two HP dc power supplies (5 V for the potentiometer and 10 V for load cell) were used as excitation voltages and they were driven from a generator.

The output voltages from the transducers were digitized and stored by a datalogger (21X micrologger Campbell Scientific Inc.). This is a programmable datalogger capable of operating in -40°C. the input ranges of each channel are user-selectable. For example, in the case of the displacement transducer (potentiometer) a full scale range of 5 V gave a resolution of 0.666 mV. The test data of 20-30 s duration for each indentation was stored in different storage locations so that they could be separated from subsequent tests. The datalogger was programmed to sample at 25 Hz. After two indentation tests the acquired data was dumped to a compatible cassette recorder through an interface board. A microcomputer (COMPAQ2) was used to read the data from the recorder for preliminary analysis and to store it in 360 k byte floppy diskettes.

3. TEST PROCEDURE

A trench, approximately 1 m deep and 1.5 m wide, was cut out of the first year sea ice using chainsaws and picks. The indentation surfaces varied from 55-75 cm, below the top ice surface, and were initially prepared by smoothing the ice wall with a chisel. The screw jacks on the ram-actuator unit were adjusted to position the unit, with the indentor head at the desired point on the ice wall. Similarly, the three linear displacement transducers were adjusted in order to measure axial distortion and depth of penetration. The excitation voltages for the load cell and displacement transducers were monitored to ensure correct output for programmed full scale ranges.

With the hydraulic power unit operating at the desired line pressure of 13.8 or 20.7 MPa, the datalogger was toggled for sampling, and the indentation proceeded when the relief valve was released.

Ancillary parameters noted in support of the above indentation test were:

1. Air temperature, surface ice temperature and ice temperature at 10-15 cm in the ice wall.
2. Wind speed and direction.
3. Weather conditions.
4. Indentor head type (number).
5. Position of indentor head relative to top surface of ice wall and its distance from adjacent indentations.
6. Dial in pressure selected and gauge pressure during indentation.
7. Thickness of powdered, crushed ice formed in the damaged area.

A video record of the entire indentation process was included for most tests. Close up photographs of the damaged indentation sites were also taken with the cracks traced out with a black felt marker. Blocks of ice samples were taken from indentation test sites for further crystallographic thin section analysis.

4. POSSIBLE SOURCES OF ERROR

1. Indentor head may penetrate the ice wall at angle creating non-measurable moments.
2. The compression/tension load cell may not be sensitive enough to measure the dynamic response of ice indentation.
3. Sampling rate of the datalogger may be inadequate.

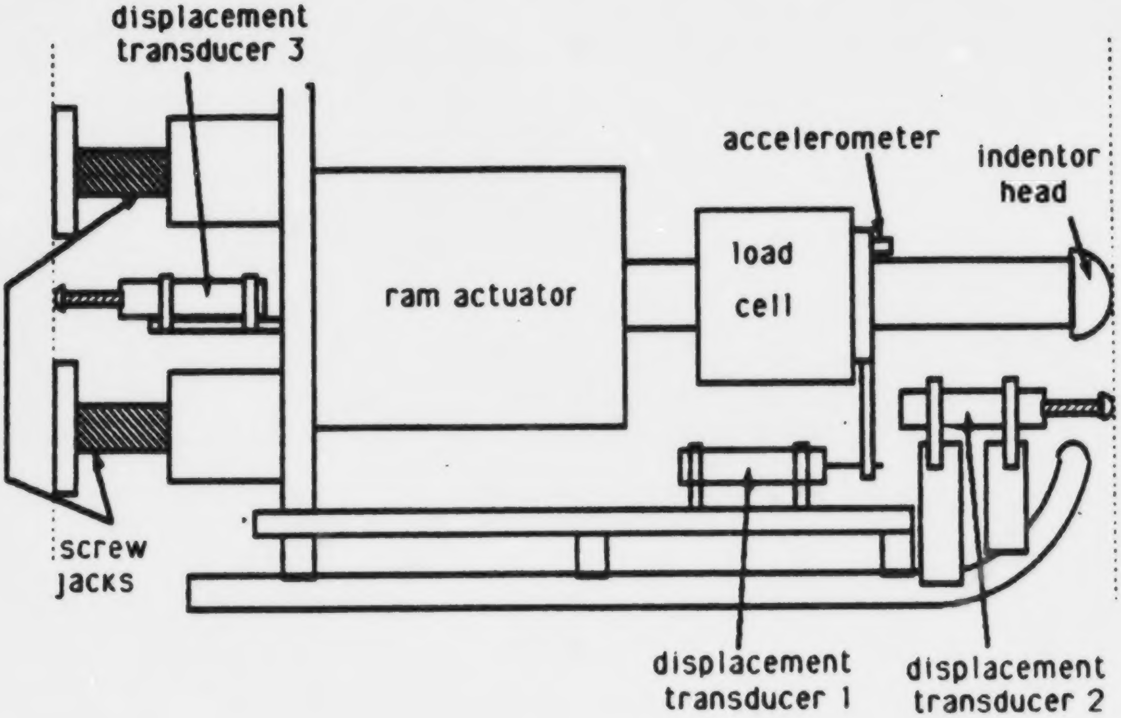
displacement transducer 3
accelerometer
indentor head
ram actuator
load cell
screw jacks
displacement transducer 1
displacement transducer 2

Figure 1. Side view of ram actuator unit

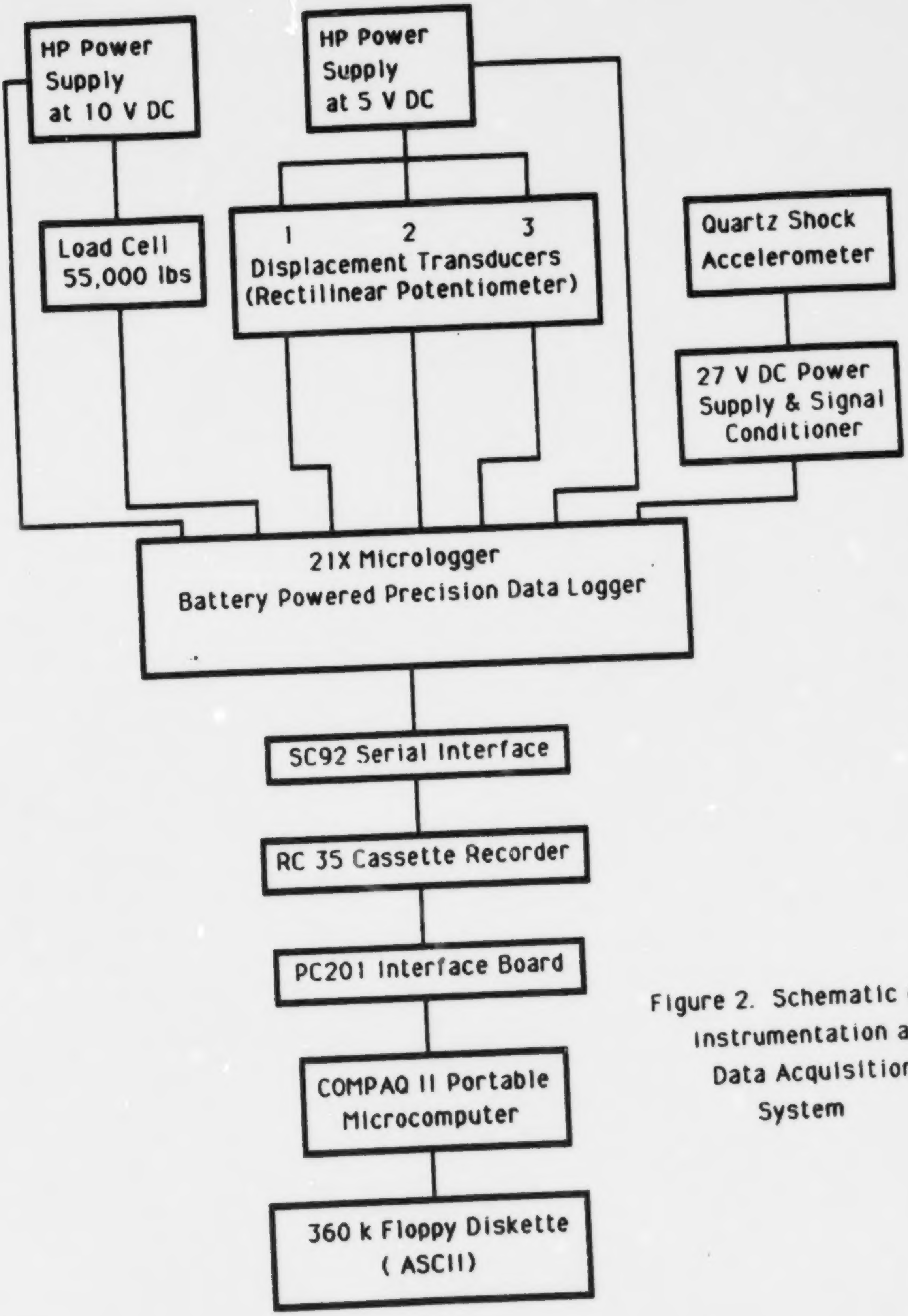
HP Power Supply at 10 V DC
HP Power Supply at 5 V DC
Load Cell 55,000 lbs
1
2
3
Displacement Transducers (Rectilinear Potentiometer)
Quartz Shock Accelerometer
27 V DC Power Supply & Signal Conditioner
21X Micrologger
Battery Powered Precision Data Logger
SC92 Serial Interface
RC 35 Cassette Recorder
PC201 Interface Board
COMPAQ II Portable Microcomputer
360 k Floppy Diskette (ASCII)

Figure 2. Schematic of Instrumentation and Data Acquisition System

Thin Sections of Indented Ice

by

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and

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Technical University of Denmark, Lyngby, Denmark

Introduction

In April 1987, a team from C-CORE and Memorial University carried out a series of tests in Resolute Bay, N.W.T., on the resistance of ice to indentation. The system was essentially composed of a 10-ton hydraulic jack with hemispherical indentors. The system has been described in detail in the previous presentation. A one-metre wide trench was dug into the ice in order to indent the flat vertical surface of the trench wall. The hydraulic jack rested on the floor and reacted against the opposite wall. The indentors acted on the ice at a point situated between 50 and 75 cm below the ice-cover surface.

Ice Characteristics

The ice encountered in the bay, outside Resolute, was of the first year sea-ice type. The cover was homogeneous with few cracks and almost no perturbations such as ridges or hummocks. The structure of the ice was clearly columnar and the orientation of the c-axis was preferential. From the pictures of the horizontal thin sections of tests #16, 19 and 25, the c-axis exhibits an approximate 45 -angle with respect to the indentation direction. This is not as clear from the pictures of thin sections from tests #11 and 12. The dimension of the crystals at the level where the indentation was carried out can be several centimetres in the direction of the platelets and almost one centimetre perpendicularly to the platelets.

Blocks of approximately 25 cm x 25 cm x 25 cm were cut with a chain saw around the hole made by the indentor. Precaution was taken to ensure that the ice would not fall apart when being removed. Against all expectations the blocks were quite solid and all cracks had effectively "healed". The blocks were shipped to St. John's and thin sections were made in the cold room of the Institute for Marine Dynamics.

Thin Sections Analysis

Not all blocks were in the same condition when they were analyzed. Blocks obtained from test areas in which small indentors had been used were usually in better condition than those from areas in which a large indentor had been utilized. In the latter case the thin sections were also more difficult to make because of the limited size of the glass plates.

Two thin sections have been made from each block. The first section was cut along the vertical plane going through the hole; the second one shows half of the horizontal plane on one of the sides of the previous vertical thin section.

The most important and obvious feature that these thin sections exhibit is the structure of the crushed ice layer. Based on the thickness of the layer itself, however, no generalities can be drawn from these pictures of thin sections; the layer varies from 5 mm (test #19) to 30 mm (test #12).

On the other hand, it appears that the demarcation between the layer and the rest of the ice is clear and rather sharp. In other words, the size of the grains varies abruptly from the crushed layer to the rest of the (virgin) ice. No rigorous measurement of the size of the grains was made, but the pictures show that the ice in the crushed layer is completely pulverized and that no individual grain can be identified. Some of the thin sections show a somewhat coarser grain size; no explanation is readily available but one might suggest that there is a relationship with the confining pressure exerted at the boundary of the indentor. The importance of the confining pressure is probably the reason for the way the ice seems to flow around the indentor (tests #11, 12, 25); distinct darker streaks parallel to the surface of the indentor can be seen on these thin sections.

Most of the thin sections essentially show interactions which can be qualified as being of the ductile type. Only a few exhibit cracks radiating from the indentor, creating interesting wedges into the virgin ice. When cracks are formed, it seems that the ice tends to recrystallize along these cracked surfaces as encountered in confined tests (Nadreau, 1985).

Conclusion

It is interesting actually to "see" the structure of the ice, once it has been indented. Even if some pulverized ice was expelled from the ice during the test, no layer of "loose" snow or crushed ice could be identified at the bottom of the hole. Undoubtedly, the conditions of pressure and temperature experienced by the ice around the indentor preclude the creation of voids between the grains which are formed during the process. Instead, the ice is virtually flowing around the indentor and remains highly cohesive once normal pressure is resumed.

Reference

Nadreau, J.P. (1985) "Lois de comportement et de fluage de la glace granulaire simulée de crêtes de pression". Ph.D. thesis, Laval University, Quebec City, Quebec.

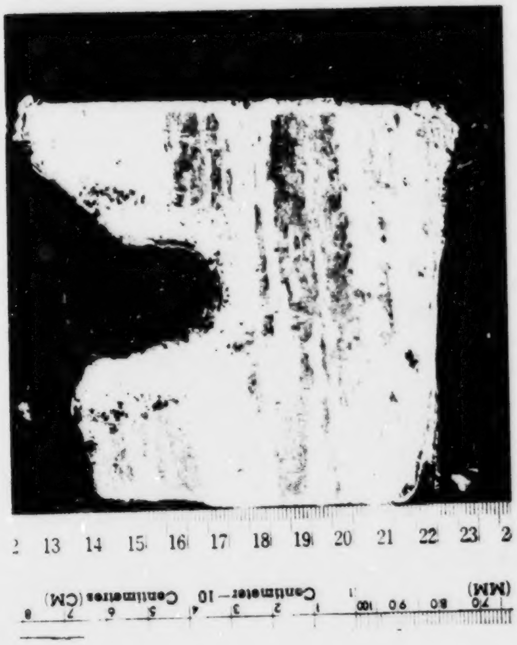
13 14 15 16 17 18 19 20 21 22 23
Centimeter—10 Centimetres (CM)
(MM)

Figure 1. Test 01
Vertical thin section

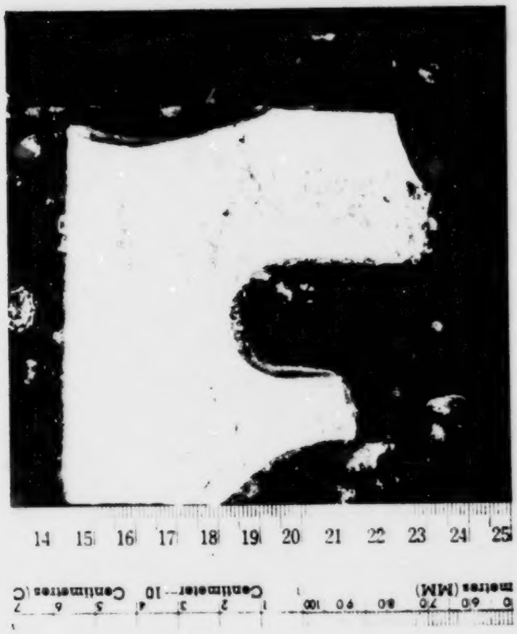
14 15 16 17 18 19 20 21 22 23 24 25
Centimeter—10 Centimetres
metres (MM)

Figure 2. Test 11
Vertical thin section

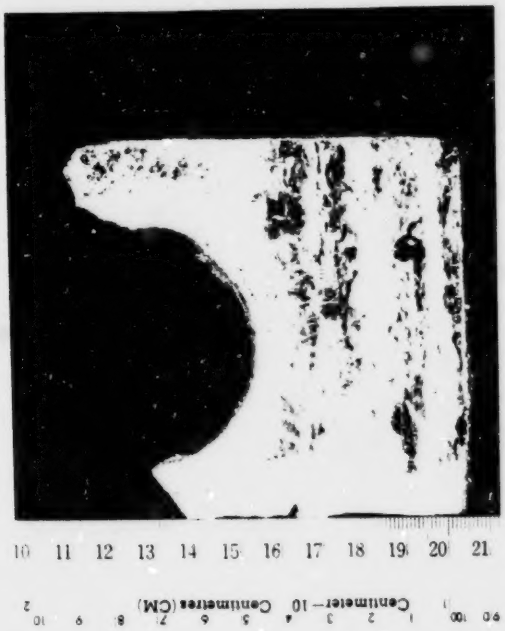
10 11 12 13 14 15 16 17 18 19 20 21
Centimeter—10 Centimetres (CM)

Figure 3. Test 16
Vertical thin section

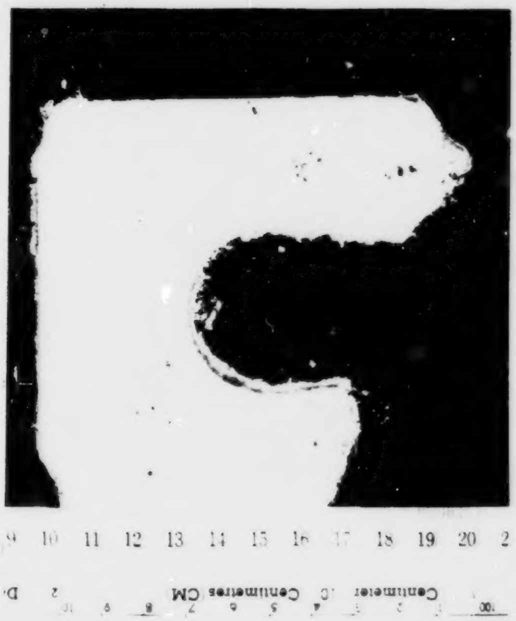
10 11 12 13 14 15 16 17 18 19 20
Centimeter 10 Centimetres CM

Figure 4. Test 12
Vertical thin section

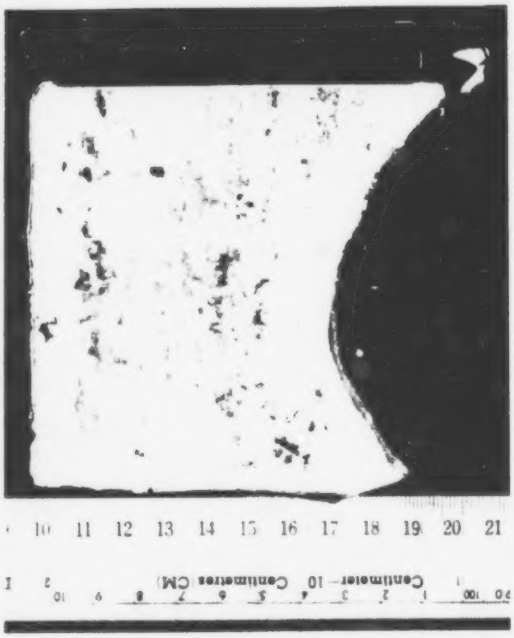
10 11 12 13 14 15 16 17 18 19 20 21
Centimeter – 10 Centimetres (CM)

Figure 5. Test 19
Vertical thin section

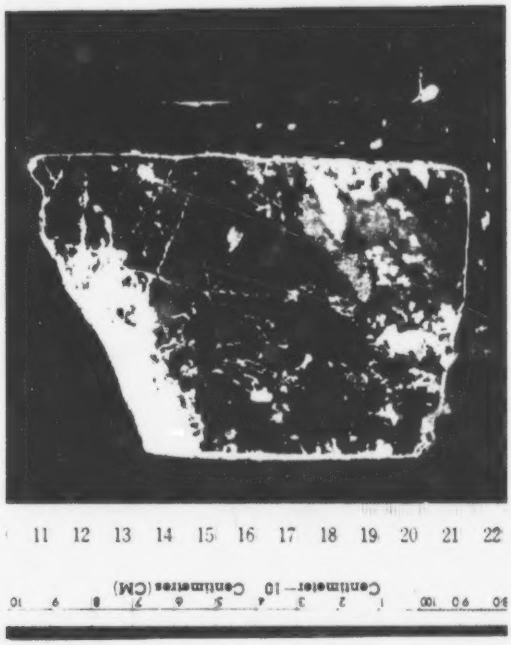
11 12 13 14 15 16 17 18 19 20 21 22
Centimeter – 10 Centimetres (CM)

Figure 6. Test 19
Horizontal thin section

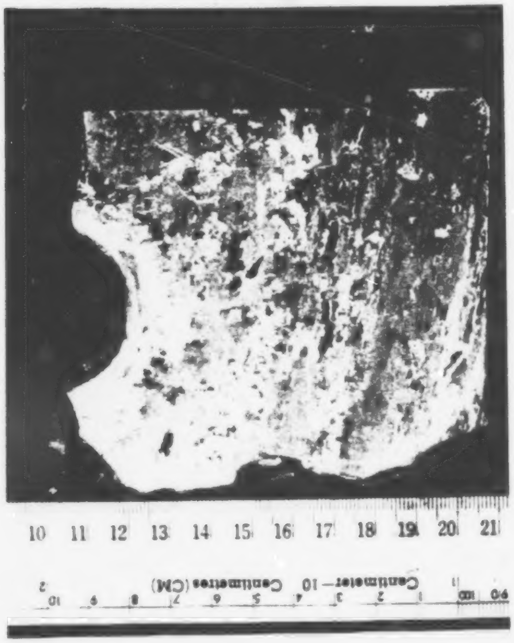
10 11 12 13 14 15 16 17 18 19 20 21
Centimeter – 10 Centimetres (CM)

Figure 7. Test 25
Vertical thin section

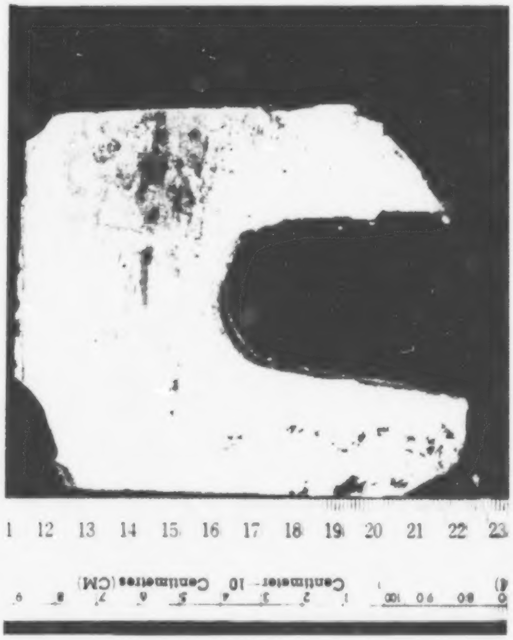
12 13 14 15 16 17 18 19 20 21 22 23
Centimeter – 10 Centimetres (CM)

Figure 8. Test 27
Vertical thin section

Session 5 - Discussion

The following questions, answers and comments formed part of the discussion period in Session 5.

C. Jebaraj:

Please comment on the pressure time history in your impact result. What is the reason for the initial rise, then fall to near zero?

S. Chin:

The result is due to the elastic ice response, then failure.

* * *

H. El-Tahan:

In the accelerometer time trace, what is the reason for the large initial fluctuation?

S. Chin:

This is a feature of all traces from this sort of accelerometer.

* * *

R. Weiss:

Do any methods exist to predict the thickness of the crushed zone in the indentor tests described?

S. Chin:

An estimate of the damaged zone beneath an indenter has been made, using the arrest stress intensity factor and hardness of ice (Parsons '89). The damage zone is that region that has experienced irreversible deformation, and contains intensely cracked ice. Outside the damage zone the ice is assumed to be elastic. The damaged zone radius is found to be 1.4 the contact radius.

Ref: Parsons, B.L., 1989 "An Estimate of the Damage Zone Beneath a Vickers Indenter on Ice", 8th Int. Conf. on OMAE, The Hague, March 19-23, 1988, Submitted.

* * *

H. El-Tahan:

My experience with using accelerometers to measure impact forces (when mounted on impact indentor) is that you get a lot of vibration giving unrealistically positive acceleration. These vibrations are shown also on your force time history giving, large tensile force. How much can we trust accelerometers in this type of application? Would it be better to use a force cell mounted, say, at the base of an ice block to measure forces directly?

S. Chin:

We employed a piezoelectric force transducer and two accelerometers in our experiment. The force transducer gave the contact pressure since the area is known while the accelerometer gave us an estimate of the global force. Of course, the accelerometer recorded the inherent vibration incurred at impact and the subsequent events after the event. The selection of the appropriate accelerometer is based on transfer function $|H(\omega)|$, frequency ω curve - within the working range of 10 to 20 khz the error is minimum.

* * *

O. Vinogradov:

Where was the force transducer and what was the possible effect of the piece between the head of the impactor and the accelerometer?

S. Chin:

These were made as rigid as possible.

O. Vinogradov:

Indentor is a structure - measure the frequencies in the structure-make sure natural frequencies are out of range of response to be measured.

* * *

J. Lever:

Referring to the continuous indentation experiment: Is the periodic nature of the force time response due to the behaviour of the ice or the indentor?

S. Chin:

I believe it to be due to the ice.

* * *

A. Tunik:

How deep was the indentation? Was this greater or less than the head of the indentor? This influences the extrusion process.

S. Chin:

When there was full envelopment of the head, the peak load increased.

S. Jones:

Do you measure ice temperature during tests?

J. Molgaard:

This is done using an infra-red sensor - there are also slip rings to accommodate a thermocouple.

* * *

I. Bayley:

Why were tension and bending moment changes recorded?

R. Gagnon:

To obtain the component of the tension due to the normal load.

* * *

H. El-Tahan:

What is the main objective of the friction tests?

R. Gagnon:

The equipment can be used to measure friction for pressures less than those causing crushing and also for direct impact with or without friction.

J. Molgaard:

The equipment can first of all be used for steady state continuous friction but more importantly for the impact between ice and ships.

* * *

H. El-Tahan:

Did the load drops that you reported possibly result from decreased contact area?

R. Gagnon:

It is perhaps worthwhile to measure contact area changes in future.

* * *

H. El-Tahan:

Was it difficult to measure crack patterns?

J. Benoit:

There were many radial cracks oriented normal to the indentor but their extent couldn't be measured in many cases.

H. El-Tahan:

Are the properties of all icebergs the same?

J. Benoit:

There are four major properties of iceberg ice that affect its strength/crushing capabilities. The first is temperature. It would appear that most icebergs in the same water and air environment exhibit a similar temperature profile. The second property is crack distribution. Most cracks in icebergs are either thermally or mechanically induced during the calving process. The crack distribution and how it affects the strength/crushing capability of an iceberg is not well known. The third property is ice crystal structure. The crystal structure of iceberg ice is random both in size and orientation even with the same iceberg. Small scale tests conducted on iceberg ice indicated that strength values are generally higher in iceberg ice with larger crystals but that these values are less than 20% higher than with smaller crystals. Orientation appears to have little affect on strength. The last property is density and it would appear that all icebergs have a similar density as it relates to ice strength.

* * *

S. Jones:

What was the nature of the crushed layer?

J. Benoit:

On removal of the indentor, the material was hard.

* * *

J. Lever:

What is the temperature effect of the outer layer of the berg?

J. Benoit:

The measured values were more conservative since the temperature was quite cold. Also, the berg may break apart.

* * *

B. Parsons:

Have pressure curves for concrete (i.e. GBS) been researched?

J. Benoit:

Not to my knowledge.

* * *

B. Parsons:

What kind of ice was used for the friction experiments?

R. Gagnon:

To date only freshwater ice, grown in IMD's coldroom, has been used. We plan to test pond ice, sea ice, iceberg ice and model ice (EGAD) in future experiments.

* * *

Brief Presentation by J-P Nadreau

- Indentation tests at Resolute
- Thin sections of ice shown
- Spalling initially
- More microcracks where the confinement is less - this is well shown
- There was evicence of flow of the crushed material

* * *

A. Tunik:

This is evidence of the difference between shallow and deep penetration.

* * *

Question:

Is there any way of predicting the thickness of the crushed layer?

B. Parsons:

Yes. The ratio of the radius of the damage zone to the contact radius is approximately 1.5.

SCALE EFFECTS (PHYSICAL & ANALYTICAL)

SESSION 6

Scale Effects in Ice-Structure Interaction:

Analytical Aspects

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Faculty of Engineering and Applied Science
Memorial University of Newfoundland

General Comments

Contact areas for ice-structure interaction in the case of full scale arctic structures are typically of the order of several hundred square metres whereas laboratory scale experiments may involve areas of a hundredth of a square metre or less. Thus a factor of 10^4 or more can apply to the dimensional scaling between these two extremes. It is perhaps not surprising that a difference is found in average contact pressures in the two cases, given that most ice failure involves brittle fracture processes. The values would typically vary from as high as 10 MPa for the small scale, to values in the range 0.1 to 1 MPa for the full scale. In a general sense, the larger the volume of failed material, the higher the probability of a flaw in the particular volume under consideration, given a "population" of randomly distributed flaws in the material. It is worth noting that ductile failure relationships (i.e. not involving material degradation) do not show a scale effect; for example, the relationship for indentation pressure based on plasticity theory is $p = k\sigma_y$, where k is a constant and σ_y = uniaxial yield strength. This does not indicate any change in average pressure with scale, since $k \approx 3$, a constant.

The principal candidate theory for dealing with scale effects is that based on a statistical distribution of flaws. This kind of analysis can be adapted to consider splitting, spalling, and the initiation of flexural failure. In the latter case, the "flaw" would relate to local areas of flexural weakness, which could result from geometric variations and imperfections (see Hallam et al, 1987). In general, non-simultaneous failure can also contribute to a scale effect since the peak load will only be experienced at certain isolated points where the failure is taking place. In the crushing mode, for example, certain zones would be extruding previously crushed ice at pressures far below the peak value and the average pressure across the structure would consequently be far below the peak local value. Mixed modes of failure can also occur, complicating the picture further.

Some of the possible failure modes resulting in scale effects are illustrated in Figures 1 and 2.

Fracture and Splitting

Since most events of importance will take place under tensile states of stress, we will concentrate in this section on mode I (opening) failures. The principles can be applied to all stress states by the use of techniques such as the J-integral method, where the energy released by extending a crack under any state of stress is computed and compared to the energy required to form the new surface (see Cormeau et al, 1984).

A crack in a tensile stress field will propagate when the stress reaches a critical value given by:

$$\sigma = \sqrt{\frac{EG_{IC}}{\pi a}} \tag{1}$$

where a = half crack length,

E = elastic modulus (plane stress),

G = energy required to create a unit area of crack (two surfaces), and

G_{IC} = value of G for mode 1 failure.

The original Griffith concept suggested the use of surface energy for G, but it has been established that work is also expended in creep (plastic) deformation in the crack tip zone. Ice is brittle enough to make the assumption that this zone is small and to include the work in the energy requirement, that is, in G. For analytical purposes, it is appropriate to calculate the energy released during the perturbation of a crack length using linear elastic fracture mechanics (LEFM).

For a sharp crack in a wide plate under tension, the stress intensity factor K_I is given by:

$$K_I = \sigma\sqrt{\pi a}, \tag{2}$$

i.e. all stresses in the region of the crack are amplified in proportion to $a^{1/2}$. Experimentally it is found that the stress at which a crack becomes unstable occurs at a value of $K_I = K_{IC}$, which is essentially a material constant.

Combining equations (1) and (2), we have (with the occurrence of a fracture event):

$$K^2_{IC} = EG_{IC}. \tag{3}$$

Recent measurements of K_{IC} for sea ice yield values in the range 0.1 - 0.14 MPa $m^{1/2}$ (Timco and Frederking, 1985). Taking E = 10 GPa, which is appropriate for high loading rates and the absence of flaws and no brine inclusions (since discontinuities are to be accounted for by fracture mechanics), we have

$$G_{IC} = 1 - 2\ J/m^2.$$

These values are similar to those for glass, which are in the range of 1 - 4 J/m^2 (Tetelman and McEvily, 1967).

If we take failure as occurring at $(a^{1/2}\sigma)$ = constant, we can think of a stress "amplified" by the square root of flaw size. This is illustrated in Figure 3. The general trend of a large set of experimental values in the literature is shown in a graph published by Sanderson (1986), Figure 4. It is expected that the flaw size will increase with the contact area, and with the inclusion of field data in the results at higher contact area. Is is also well known that the Hans Island experiments have resulted in substantial reductions in design ice pressures.

It should be noted that some particular comparisons of small and large scale strengths (Wang and Poplin, 1981) of sea ice do not show a trend of the kind noted above. The study mentioned did not explicitly recognize the role of flaws in the possible scale effect relationship.

All of the factors above raise several questions which have to be addressed, for example:

(1) What is the flaw size, the orientation and the density distribution in sea ice?

(2) Are there several distributions, e.g. one for small local cracks, another for large extensive cracks, and so on?

The size, orientation and density distribution of flaws, coupled with the stressed volume, which is dependent on the indenter/structure size, suggest a probabilistic approach to the problem. Indeed, there may be a non-zero probability of the event "no significant flaws" - as evidenced in the Exxon study (Wang and Poplin, 1981).

A probabilistic approach should provide information on:

(a) The best relationship for mean pressure given basic flaw distribution parameters density, orientation, size and possibly shape.

(b) The spread of one's estimate of (a) above - note the band of values in Figure 4.

Probabilistic Theories of Strength: Shortcomings of Weibull Method

It is appropriate to concentrate on materials which contain distributions of cracks and flaws, but which are homogeneous, in the sense that the statistical parameters of the defect distribution are not judged to be a function of position in the ice mass.

A survey of standard text books in materials science reveals a paucity of information on statistical strength theories. The most commonly used model is that of Weibull (Hudson and Fairhurst, 1969). Although we shall show in the following that Weibull's distribution can also be derived on the basis of extreme-value theory, this was not the case in the work of Weibull. He considered a series of elements or links (Figure 5) - "identical" in the sense that they have random strength Y (in units of stress) with the same probability distribution $f_Y(y)$ and cumulative distribution function (or CDF) $F_Y(y)$. The probability of survival of an element is $[1 - F_Y(y)]$ and the probability of survival of the system is given by $[(1 - F_Y(y)]^n$, if the assumption is made that each "link" or element is independent of the others.

If W is the (random) strength of the assembly or system, then the probability of system survival is:

$$[(1 - F_W(w)] = [1 - F_Y(w)]^n. \tag{4}$$

This follows since $W = \min(Y_1, Y_2, Y_3, \ldots Y_n)$. Weibull then wrote the expression for $F_Y(y)$ as:

$$F_Y(y) = 1 - e^{-\phi(y)}, \tag{5}$$

and choose $\phi(y)$ to be a power law of the form

$$\phi(w) = \left(\frac{w - w_{min}}{w_0}\right)^m , \tag{6}$$

where w_0 and m are constants.

For constant stress, we obtain the usual form of the Weibull CDF:

$$F_W(w) = 1 - \exp\left[V\left(\frac{w - w_{min}}{w_0}\right)^m \right], \tag{7}$$

where V is the volume.

This distribution can also be derived, under wide conditions, as an extreme value distribution ($n \to \infty$) of the minimum value of Y_1, with arbitrary "parent" CDF $F_Y(y)$. As n increases, the extremal distribution depends more and more on the shape of the "parent" near $y = Y_{min}$.

There are many ramifications of the Weibull model, including heterogeneous stress states, stress versus strain control in testing and in reality. It leads quite simply to the size effect rule

$$\frac{\text{median failure stress 1}}{\text{median failure stress 2}} = \left(\frac{V_2}{V_1}\right)^{1/m} \qquad (8)$$

for volumes of material equal to V_2 and V_1. This has been used by Iyer (1983) in studying size effects in ice.

The key aspect that we have emphasised in the first sections of the paper is that fracture is initiated by a criterion related to:

$$(\text{stress})(\text{crack length})^{1/2}$$

and not by stress alone. Therefore, the link to the mechanics of the fracture process that is lacking in the Weibull formulation is the characterisation of flaws.

Extending this principle to an arbitrary state of stress, we must consider a flaw system, random in number, size and orientation. The latter is important because a long crack at right angles to a compressive stress may not propagate whereas a shorter crack in a tensile field at a different location or orientation could propagate, given the same external loading conditions. Therefore, the criterion for crack propagation is of the following form:

$$U(\sigma_{ij}, \theta_i, \sqrt{a}) \geq 0 \qquad (9)$$

where θ_i denotes the orientation of the crack and σ_{ij} the stress state. When orientation and crack length are treated as random - the former could be uniformly distributed over possible angles in space - Eq. 9 results in a CDF for U, i.e. $F_U(u)$.

A very promising direction of research is to assume that the number of defects in a given volume of material, say V, is Poisson-distributed, i.e.

$$p_N(n) = \frac{e^{-\nu}\nu^n}{n!}, \; n = 0,1,2,\ldots \qquad (10)$$

where ν = expected number of defects in volume V. If failure takes place when the value of U is a maximum, i.e. in the case of

$$Z = \max U_i \qquad (11)$$

where $i = 1,2,\ldots,N$, where N is random, with distribution given by equation (10), then

$$F_Z(z) = \exp[-\nu(1-F_u(z))]. \qquad (12)$$

This approach was implemented taking into account a non-homogeneous stress distribution in loaded ice floes, by Maes et al (1986). The methodology can be extended to the case of exchangeability (see Jordaan and Maes, 1985). Numerical analysis was used to determine the stress distribution; previously a deterministic approach to floe splitting, using finite elements, had been developed by Cormeau et al (1984). Some results of the statistical theory are shown in Figure 6, compared to flexural strength results of Croasdale (see Maes et al, 1986).

Non-simultaneous Failure

There are two reasons why failure is unlikely to be simultaneous across the ice-structure interaction surface. The first reason is termed systematic and the second random. To illustrate the first, consider the spherical indenter illustrated in Figure 7; the state of stress in the zone near the centre of symmetry (Zone "A" in Figure 7) is given approximately by the line $\sigma_3 = 0.80\sigma_1$ of Figure 8 (see Jordaan and McKenna, 1988). This is in the zone of pure creep of Figure 8, and a damage failure is unlikely to be initiated. Therefore it is much more likely that failure progresses from the zone near the surface of the ice as illustrated in Figure 7.

Given a large enough interaction surface, it is likely that failure could be initiated independently in several zones. This approach, based on the statistics of averaging over several such zones, has been pioneered by Kry (1980, for example).

The concept of cycles of pulverisation of ice and clearing of the products has been developed to explain cyclic dynamic load (e.g. Jordaan and Timco, 1988). This approach could be combined with the statistical approach of Kry; there are however indications that simultaneous failures can take place; see the analysis by Jefferies and Wright (1987) termed "phase-lock".

Conclusions

1. Some basic methods for the use of probabilistic fracture mechanics are available. Little information on flaw distributions in natural ice is in evidence.

2. The analysis of non-simultaneous crushing has been considered by several workers, and some basic tools for this approach are available in the literature.

3. Useful work on flexural failures resulting from variations in

cross-sectional profile has been done by Hallam et al (1987).

4. The subject of spalling has received little attention.

5. Scale effects related to crushing have not been studied in any detail. The size distribution of the resulting pieces may well be important.

Acknowledgements

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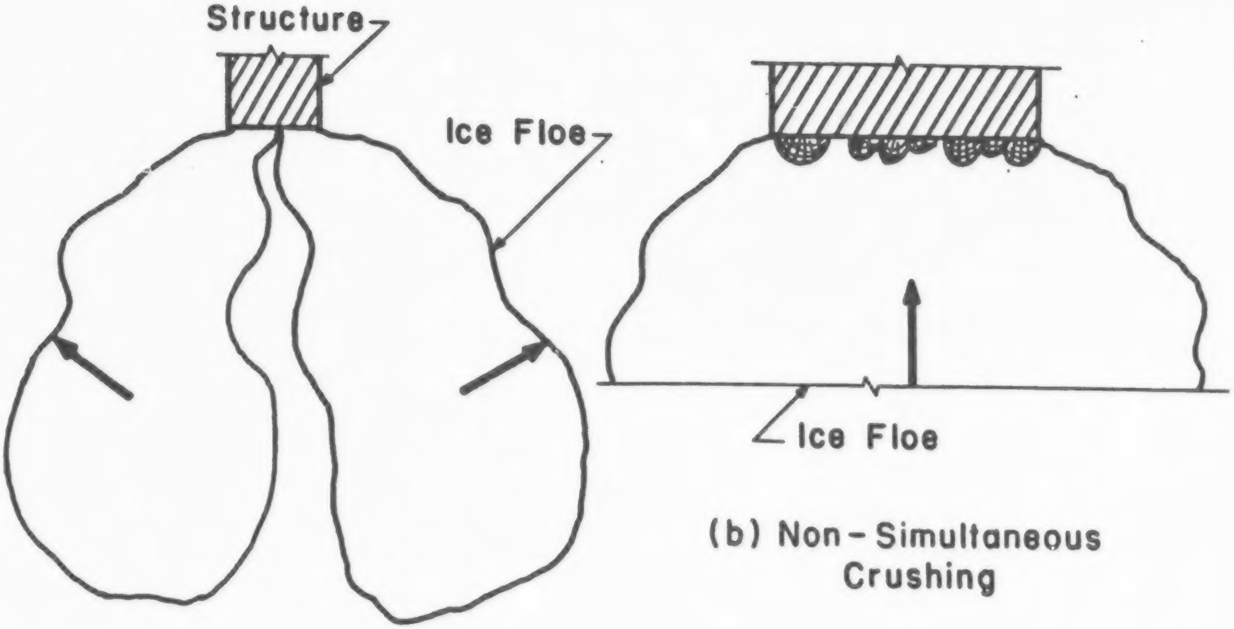
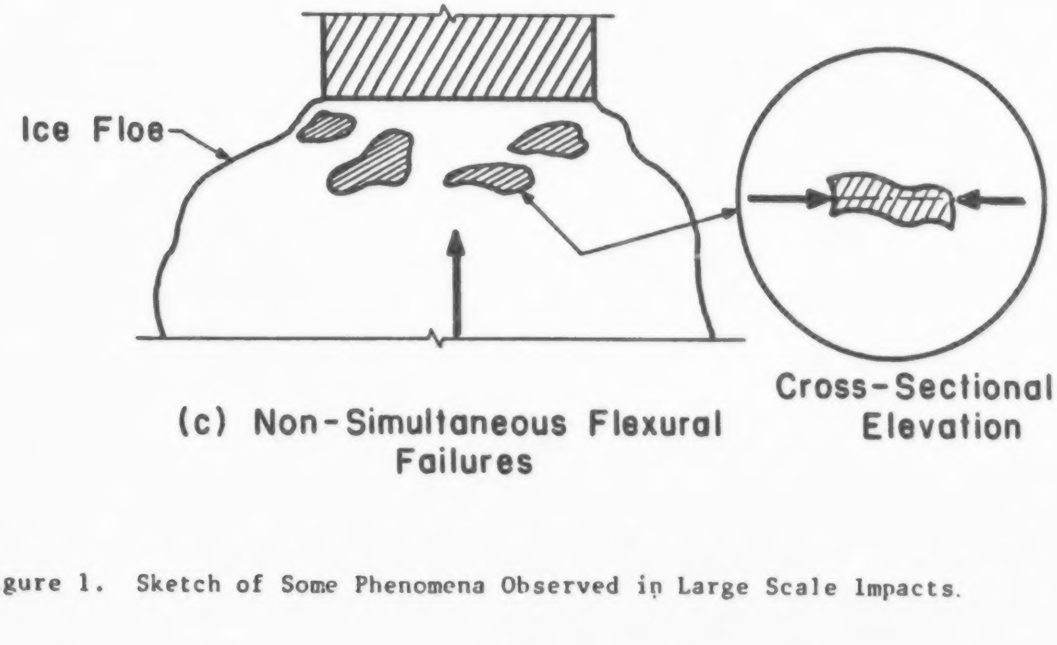

Structure
Ice Floe
Ice Floe

(a) Splitting

(b) Non-Simultaneous Crushing


Ice Floe
Cross-Sectional Elevation

(c) Non-Simultaneous Flexural Failures

Figure 1. Sketch of Some Phenomena Observed in Large Scale Impacts.

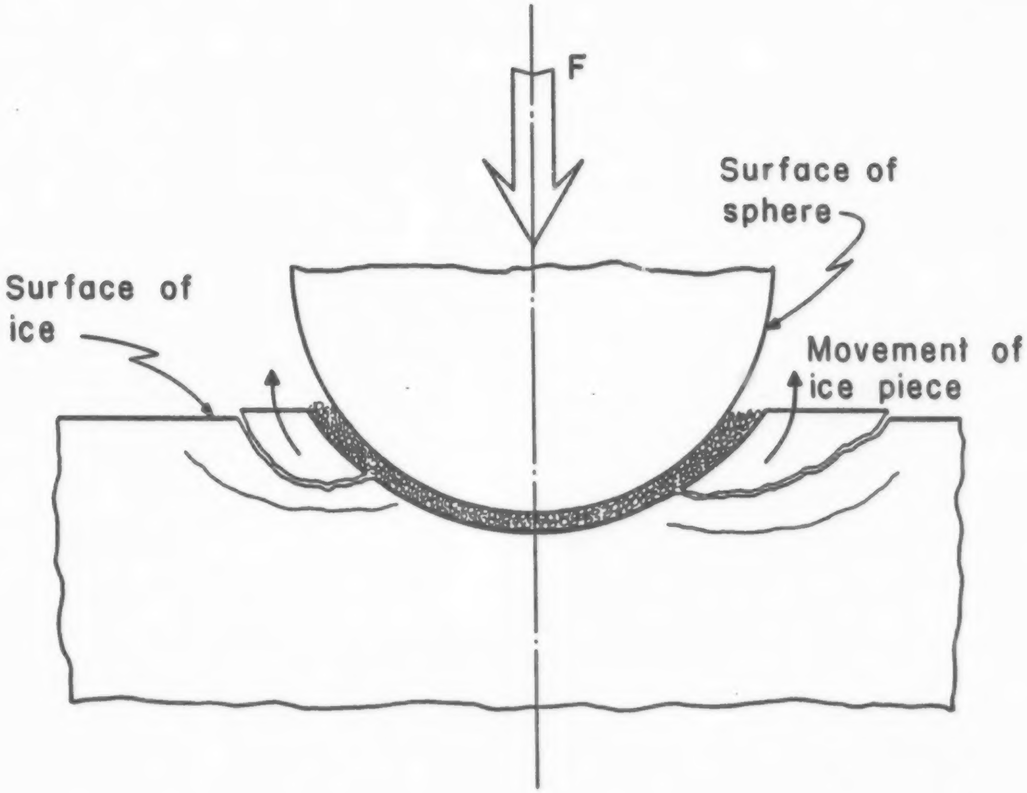

F
Surface of sphere
Surface of ice
Movement of ice piece

Figure 2. Crushing and Spalling Under a Spherical Indenter

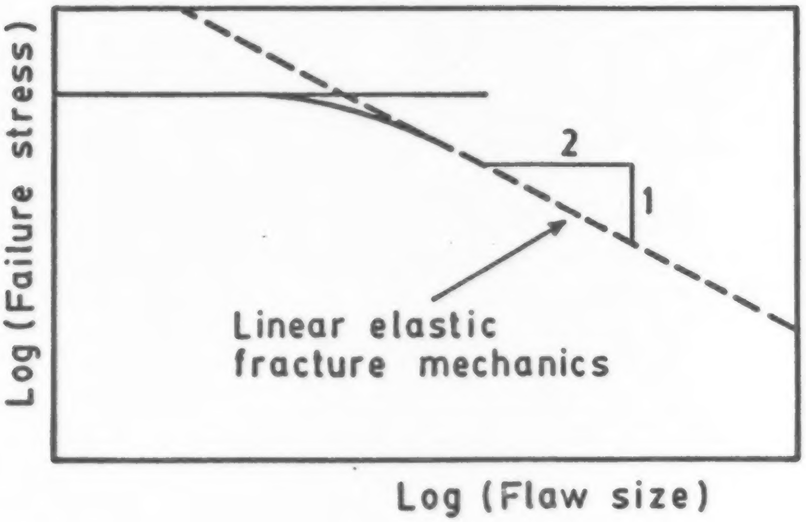


Figure 3. Scaling Based on Fracture Mechanics

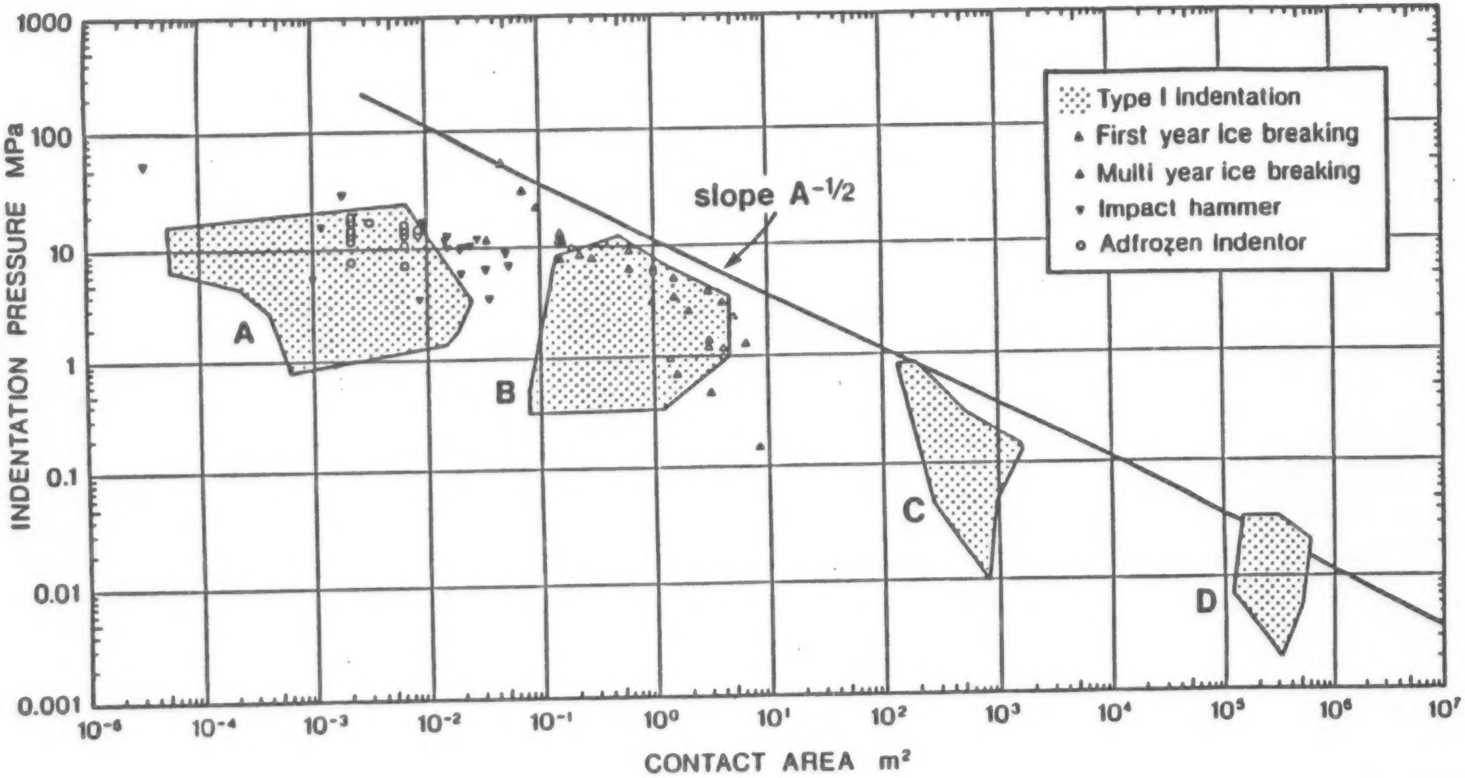


Figure 4. General Trend of Pressure-area Curve, with Data Groups (Sanderson, 1986)

A. Laboratory Tests

B. Medium-scale In Situ Tests, Lighthouses and Bridge Piers

C. Full-scale Arctic Islands and Structures

D. Meso-scale Models

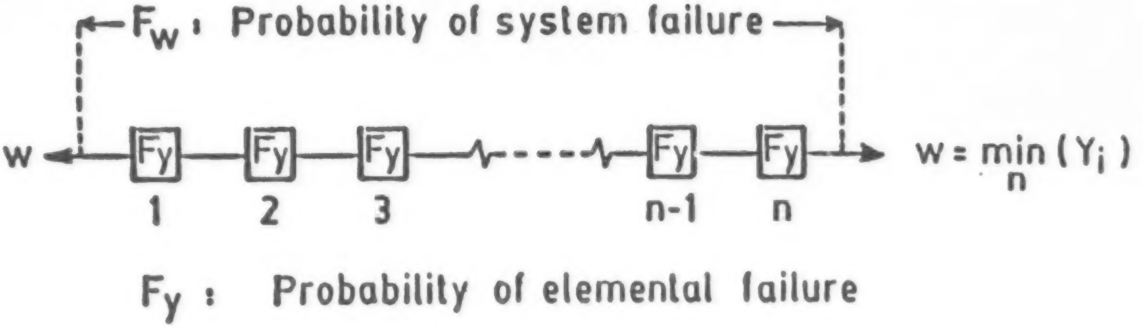

F_W : Probability of system failure
w
Fy
1
2
3
n-1
n
$w = \min_n (Y_i)$
F_y : Probability of elemental failure

Figure 5. Series of Elements in Weibull's Model

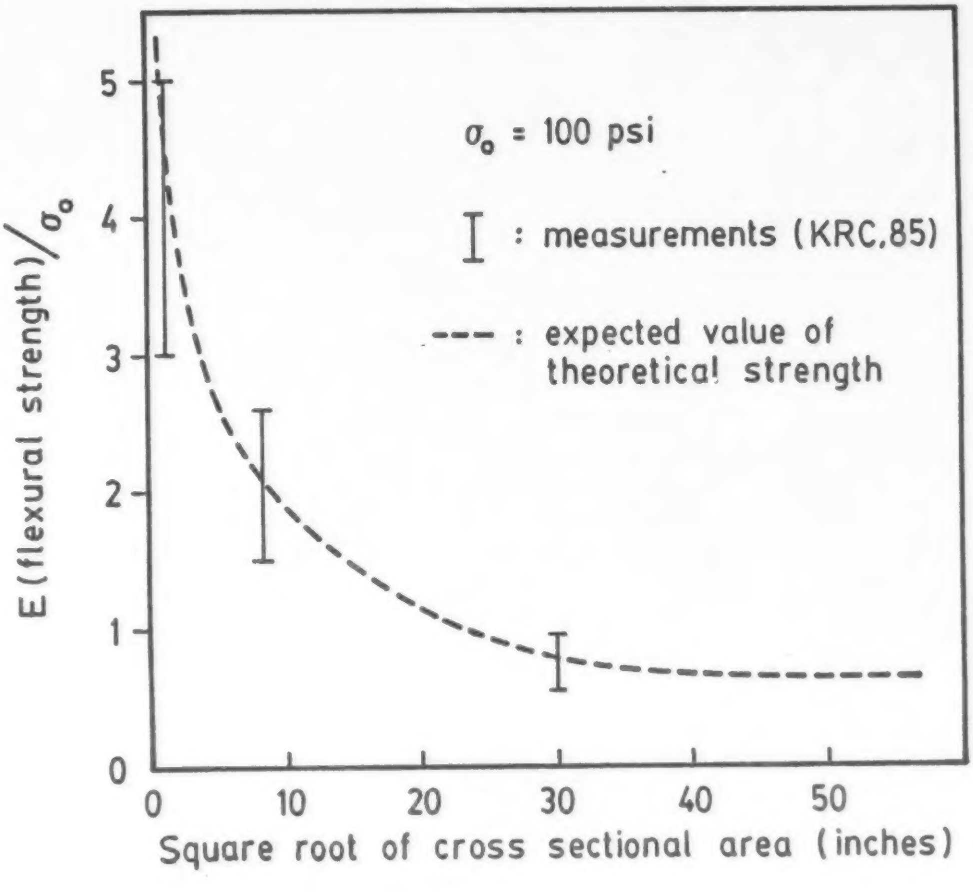


Figure 6. Comparison of Theory with Measurement of Tensile Strength (Maes et al, 1986)

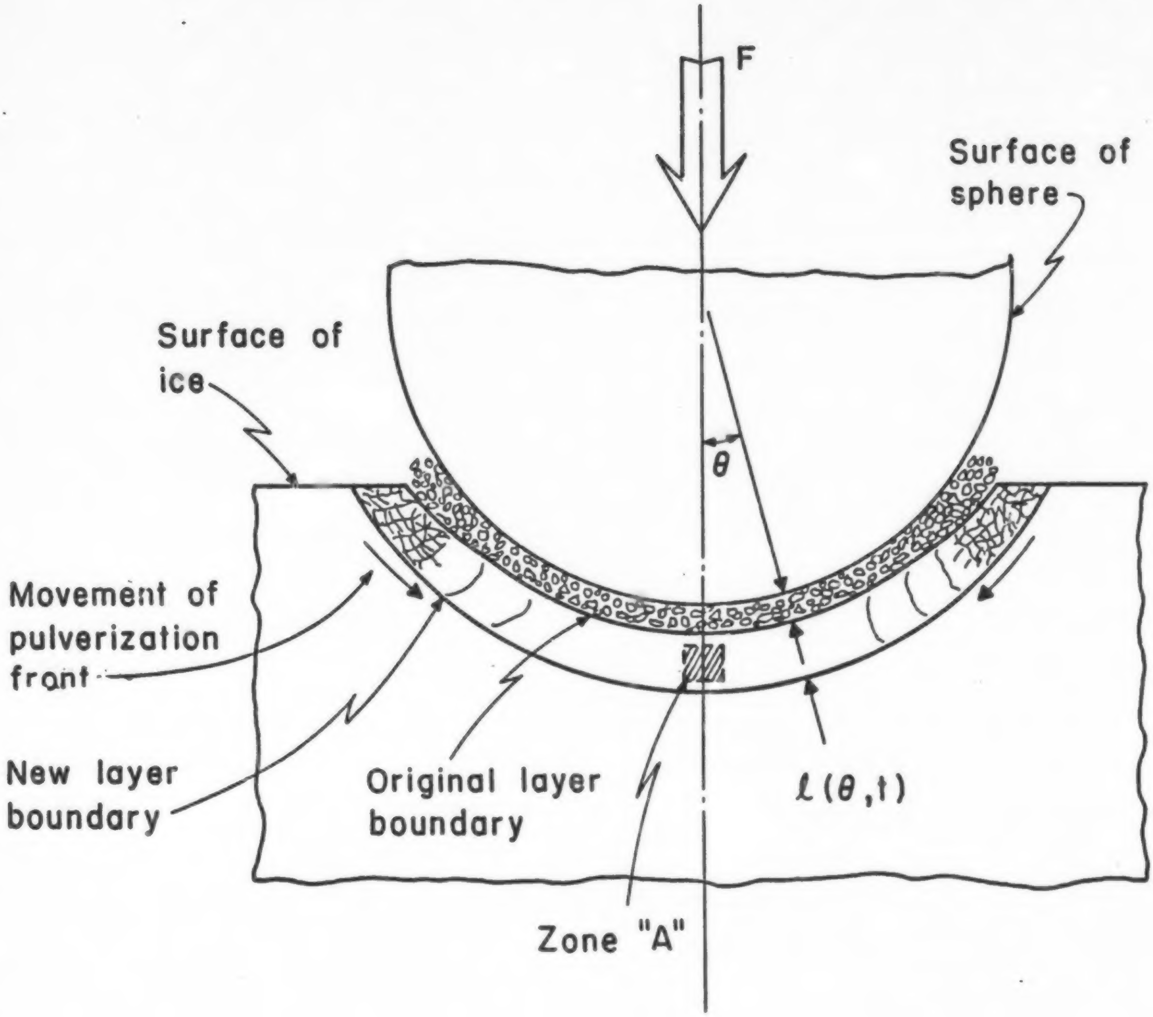

F
Surface of sphere
Surface of ice
θ
Movement of pulverization front
New layer boundary
Original layer boundary
$\ell(\theta,t)$
Zone "A"

Figure 7. Failure Under Spherical Indenter Initiated in Zone Near Ice Surface (Hypothetical)

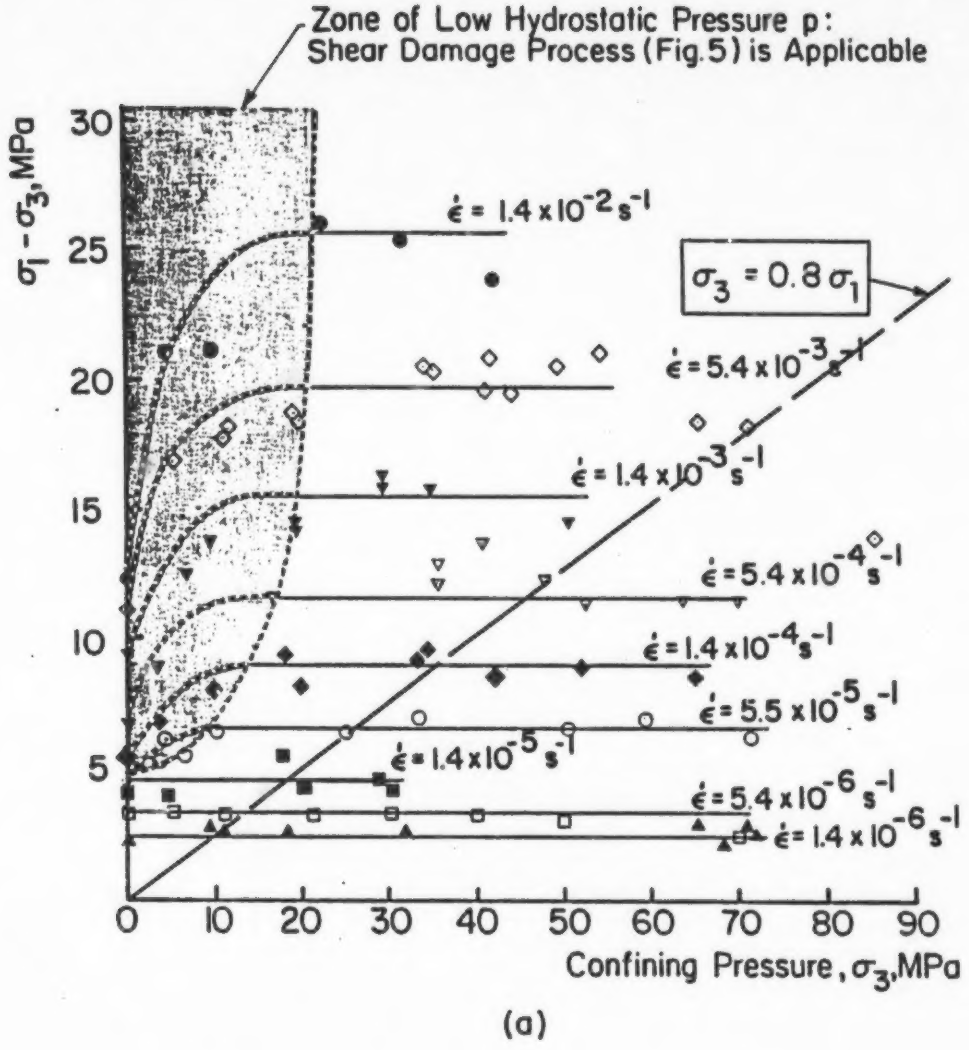


Figure 8. Deviatoric stress, $\sigma_1 - \sigma_3$, as a function of confining pressure, σ_3, in triaxial experiments on polycrystalline ice (from Jones, 1982).

SCALE EFFECTS IN ICE

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OVERVIEW

This paper discusses the scale effect in ice using a number of different approaches.

First, the evidence which supports a scale effect is reviewed by looking at the measured ice loads on structures as a function of both contact area and aspect ratio.

Next, the strength of ice is reviewed as measured using different sizes of samples for compressive strength, flexural strength, tensile strength and impact strength.

Following this, the sample size effect is examined in several other materials including coal, rocks and concrete.

A number of explanations have been put forward to explain this size effect in materials. In the next section these are briefly reviewed.

Finally, the failure modes in ice are discussed with an emphasis on their influence in creating an apparant size effect in ice.

1.0 THE SCALE EFFECT IN ICE

There has been considerable discussion on the scale effect in ice, but the strongest evidence for a scale effect are the curves presented by Tim Sanderson in his review paper in 1986. These curves are shown in Figures 1 and 2. The figures show the indentation pressure as a function of aspect ratio (figure 1) and contact area (figure 2). It is important to distinguish between these two different parameters.

There are several things which should be noted about these figures:

1. Both graphs are plotted in log-log format , covering many orders of magnitude.
2. The data is taken from a wide variety of sources and include information obtained from ice loads with sea ice, river ice, multi-year ice, and laboratory freshwater ice.

There is no doubt that the figures show a strong trend of decreasing pressure with increasing aspect ratio and contact area.

The question is, what causes this apparent general decrease in pressure ? More importantly, can we always count on this size effect when designing offshore structures?

To try to answer this question, we can examine the various parameters which could cause this behaviour. The first thing which will be examined is the size effect in ice strength.

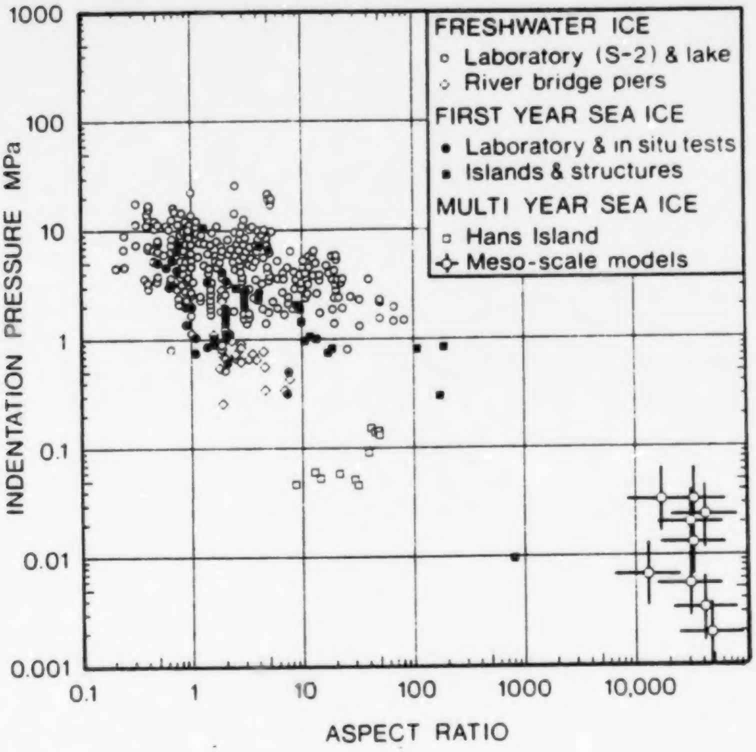


Figure 1 : Indentation pressure versus aspect ratio (Sanderson, 1986)

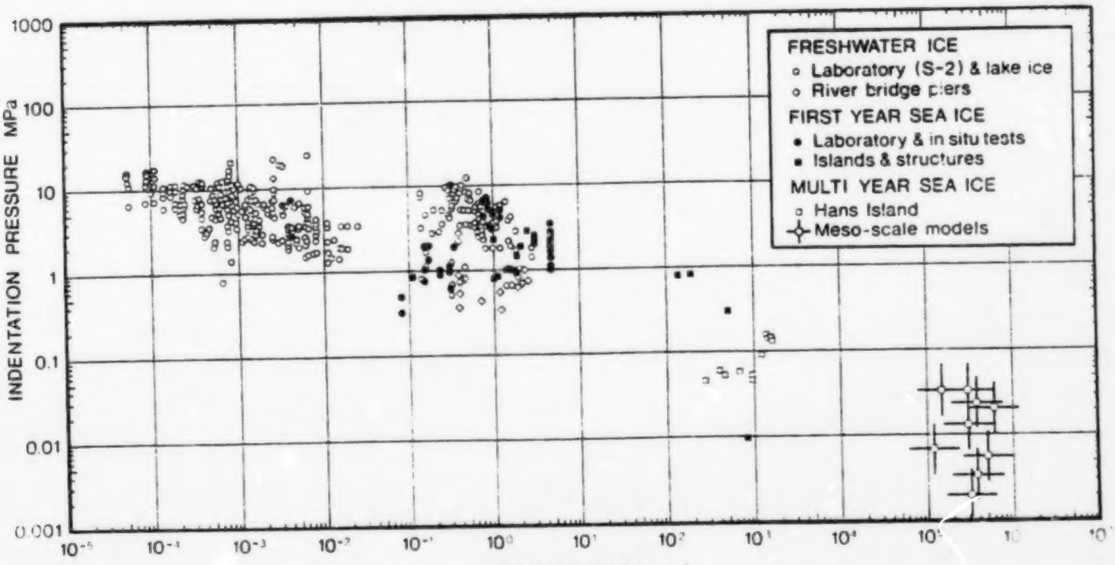


Figure 2 : Indentation pressure versus contact area (Sanderson, 1986)

2.0 SUMMARY OF STRENGTH TESTS ON ICE

There have been a number of test studies to look at the scale effect in ice. These studies have measured compressive strength, flexural strength and impact pressures.

The most thorough study of size effect in ice compression are the extensive test program carried out by Exxon, and reported in Chen and Lee (1986) and Wang and Poplin (1986). As shown in Figure 3, a field study on beams with dimensions of meters was undertaken to measure " the large scale " compressive strength. At the same time, ice samples were taken back to a laboratory setting and a number of small scale tests were run to measure the ice strength in laboratory conditions. As shown in Figure 4, there was no appreciable difference in the strengths suggesting that there is little or no scale effect in compression in ice.

Results from an APOA study reported by Iyer (1983) on the compressive strength indicate a size effect (see Figure 5). Examination of the Figure, however, suggests to the author that there is in fact little scale effect. It seems that there is considerable scatter and a definite trend is not conclusive.

With regard to the flexural strength, tests by Tozawa and Taguchi (1986) suggest a size effect (see Figure 6). Again, however, the data is not conclusive. Tests reported by Weeks and Assur (1972) do , however, indicate a strong size effect (Figure 7). A comparison by Timco (1985) of all flexural strength measurements on sea ice suggest no size effect at all (Figure 8).

A study by St. John and Daley (1984) measuring the impact pressures on the USCGC Polar Sea indicates a strong size effect (Figure 9).

This review of ice strength data certainly presents conflicting information. There is nothing definite which can be said about the size effect in ice strength.

In other materials there are similar discussions on the size effect. These are briefly reviewed in the next section.

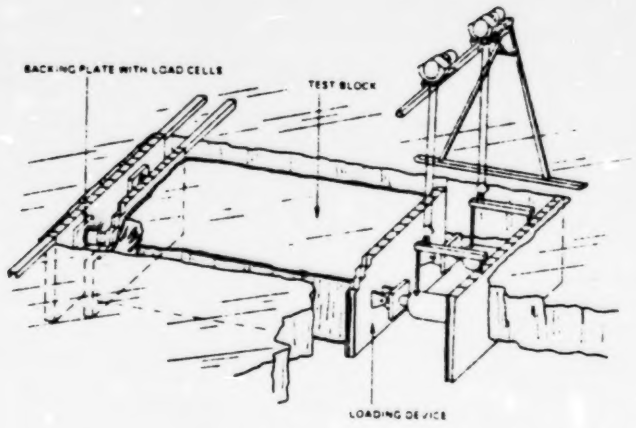

BACKING PLATE WITH LOAD CELLS
TEST BLOCK
LOADING DEVICE

Figure 3 : Test set-up for the Exxon tests (Chen and Lee, 1986)

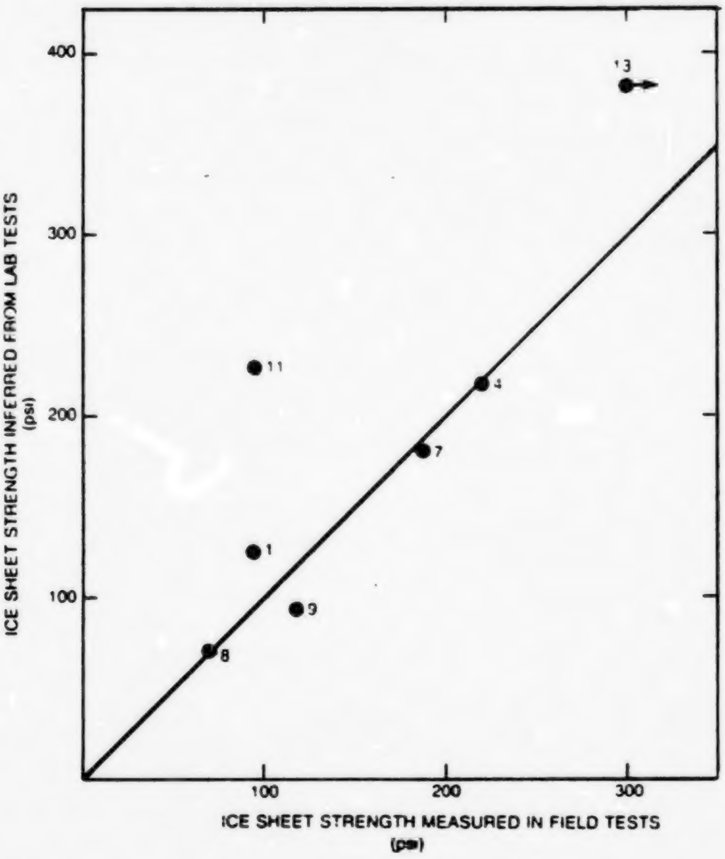


Figure 4 : Comparison of large and small scale strengths in the Exxon tests (Wang and Poplin, 1986)

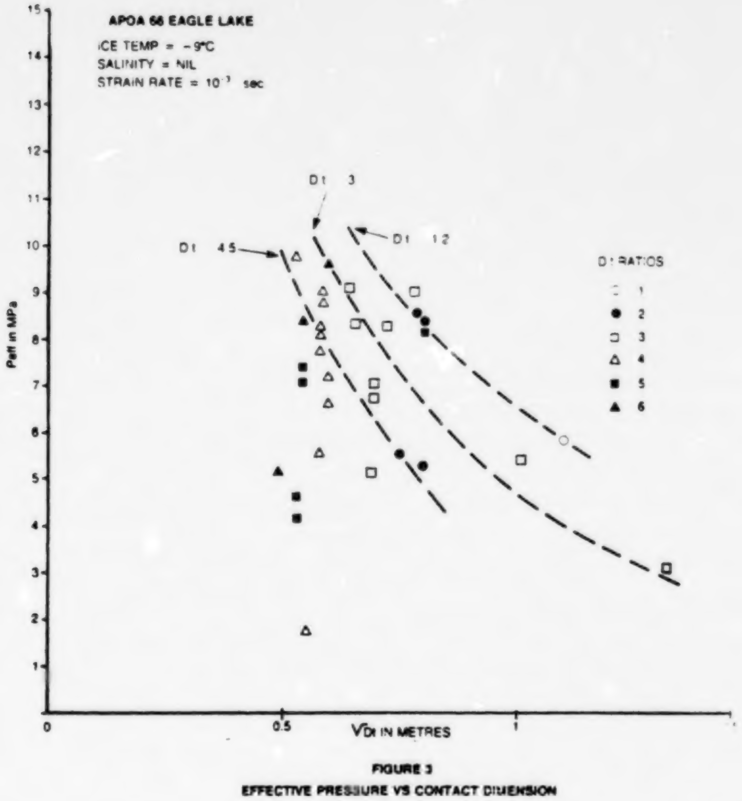


Figure 5 : Compressive strength results from Eagle Lake (Iyer, 1983)

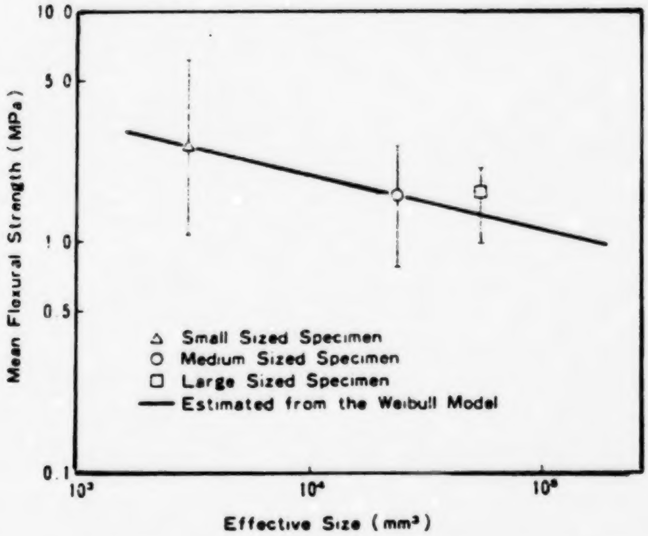


Figure 6 : Flexural strength results of Tozawa and Taguchi (1986)

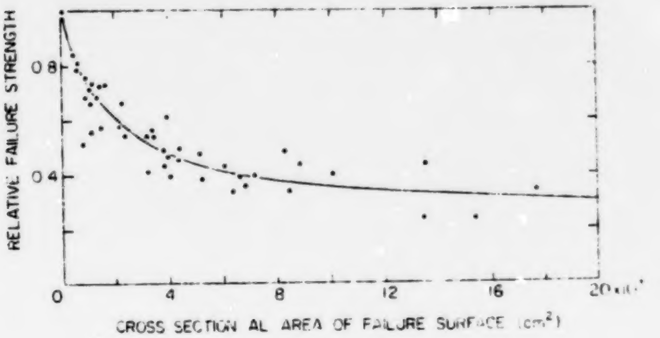


Figure 7 : Flexural strength results reported by Weeks and Assur (1972)

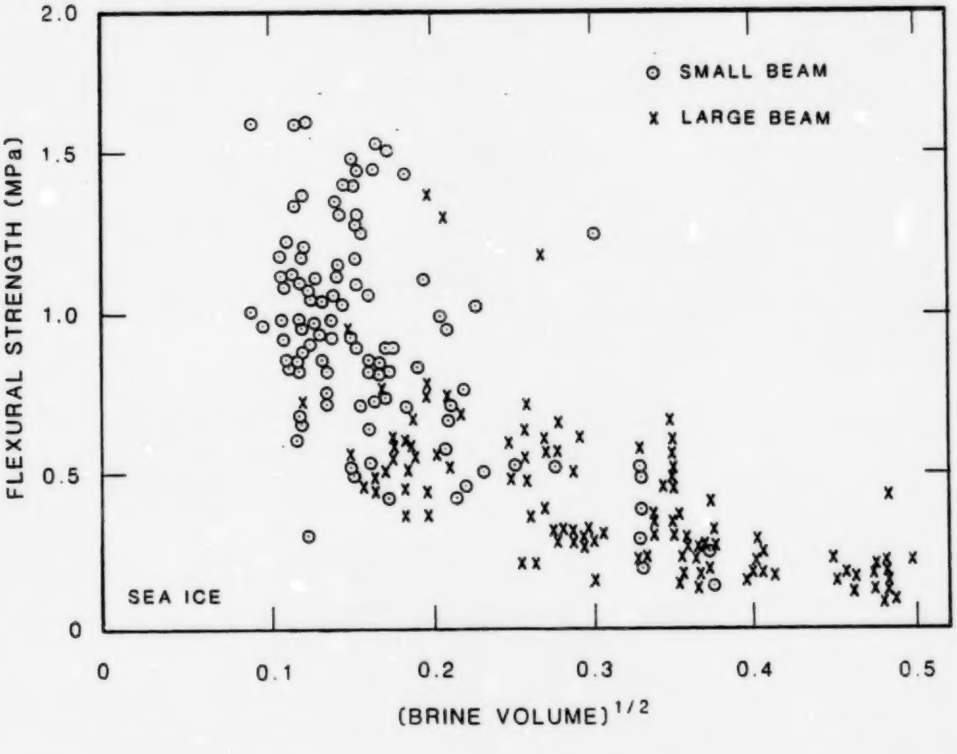


Figure 8 : Comparison of all flexural strength tests for sea ice (Timco,1985)

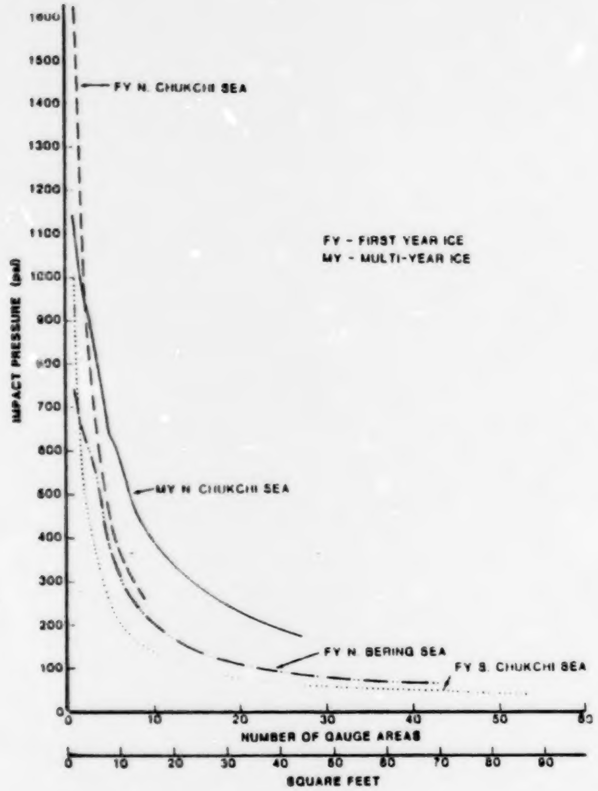


Figure 8.
IMPACT PRESSURE VS. AREA
FOR SEVERAL EXTREME EVENTS

Figure 9 : Impact pressures on the USCGC Polar Sea (St. John and Daley, 1984)

3.0 REVIEW OF STRENGTH TESTS ON OTHER MATERIALS

For many years researchers in several other disciplines have discussed the problem of the size effect in strength. Results for coal (Bieniawski, 1968; Evans and Pomeray, 1958) suggest a strong size effect for this material. Moreover, tests of strength on rocks (granite, sandstone and limestone) also indicate a size effect (Lundborg, 1968). Similarily, tests on concrete breakwater armour units by Burcharth (1981) show very strong size dependancy.

Brown (1971), however, examined the published data and suggests that it has not been conclusively demonstrated that there is a size effect in rocks. Brown suggested that most of the apparant experimental verifications are reflections of constraints imposed by the testing system and they are not intrinsic material properties. Many of the observed size effect arise from the existence of a stress gradient in the sample. Brown states that in uniformly loaded rock specimens there is not likely to be a size effect. (This is in agreement with Exxons test results for ice). Attempts to account for a size effect in the compressive strength of rocks using the Weibull theory of strength of materials has been shown by Brown to be fallacious since they generally oversimplify Weibulls original theory and apply it to situations other than those to which it was proposed.

4.0 EXPLANATIONS FOR THE SIZE EFFECT

There has been a number of explanations put forward to explain the apparant scale effect in ice. In general these can be catagorized into three separate approaches. There is no clear evidence that any one of these can explain the scale effect. More than likely the scale effect results from a combination of all three.

The explanation first proprosed by Kry (1978) looks at the ice loading on a wide structure in terms of a number of zones (see Figure 10). In looking at the time series variations of load on a structure, Kry showed that as the number of "zones" increased, there was a general smoothing of the peaks in the time series with a resulting lower peak pressure on the structure (Figure 10). In this way, a wider structure would have a lower effective pressure on it.

The second approach to explaining the size effect is related to the number of "flaws" in the ice. This approach can be subdivided into two separate explanations. The first treats the number and size on flaws which exist in a sample of ice. In general the premise in this case is that as the sample gets larger, there is an increasing likelihood of the sample containing a large flaw and causing a lower strength. As outlined by Sanderson (1986) and shown in Figure 11, there are a number of different assumptions which can be made about the flaw size distribution in ice. The second explanation related to flaws in ice considers the very large flaws which exist in ice sheets in nature. These long flaws or leads can reduce the size and confinement of ice sheets thereby lowering the load which the ice can exert on a structure. Timco (1987) performed a test series with freshwater ice to look at this effect. His results, extrapolated to full scale (see Figure 12) suggest that only a few long flaws in the ice can cause a significant load reduction.

The third explanation for the size effect is related to the number of extrinsic parameters which come into play in the whole interaction process. Brown and Gonano (1975) have outlined some of these in terms of strength testing of rocks (see Figure 13).

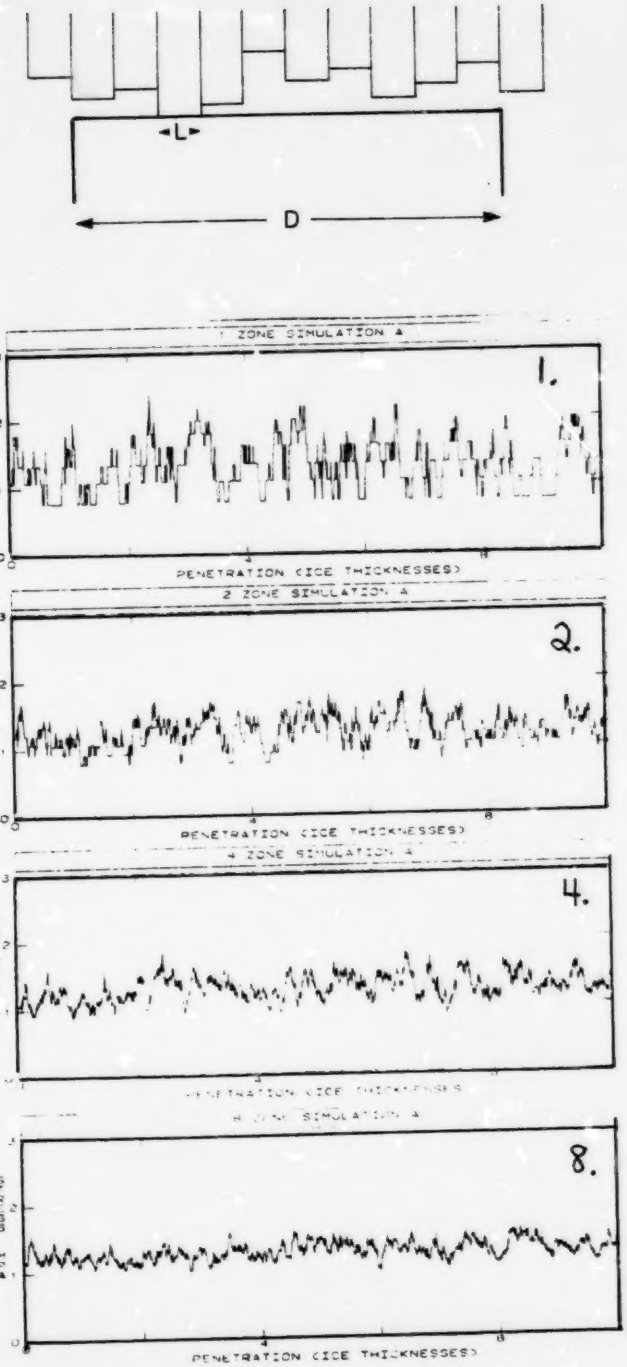
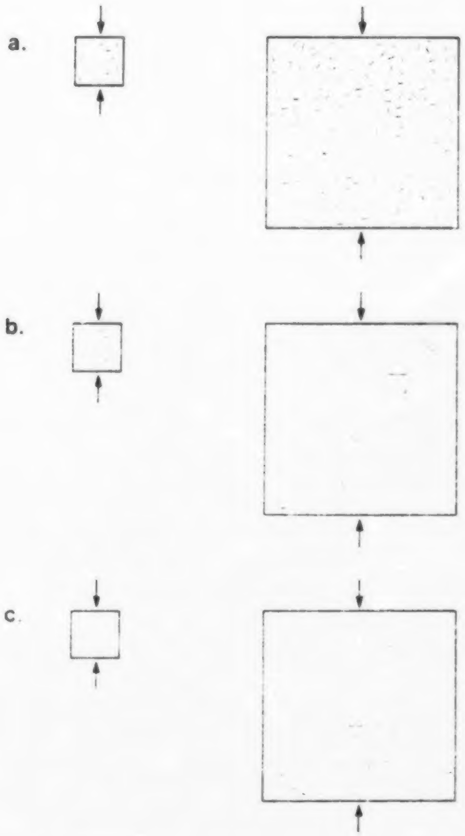


Figure 10 : Non-simultaneous contact for load reduction (Kry, 1978).



σ = constant

$\sigma \propto \lambda^{-1/2}$ or $A^{-1/4}$

$\sigma \propto V^{-1/b}$ or $A^{-3/2b}$

Scaling assumptions: (a) Material remains uniform

(b) Geometric scaling of sample and material

(c) Statistical distribution of flaws

Figure 11 : Small flaws in ice with scaling assumptions (Sanderson, 1986).

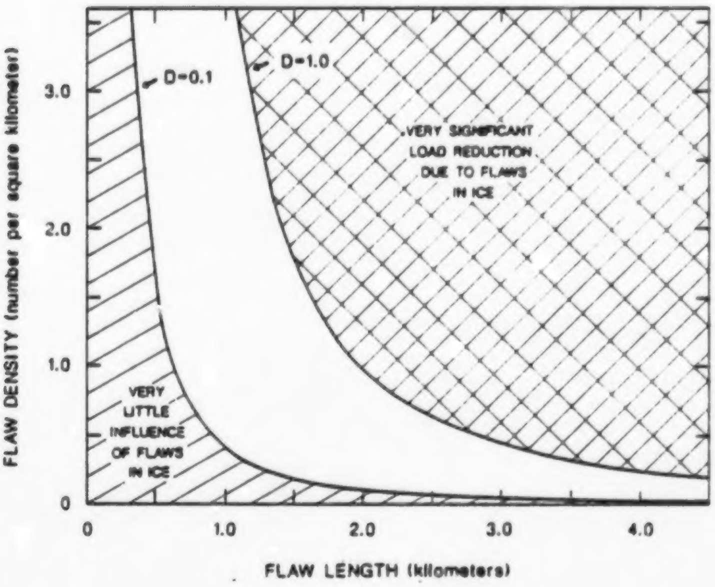


Figure 12 : Predicted flaw densities and flaw lengths for load reduction (Timco, 1987).

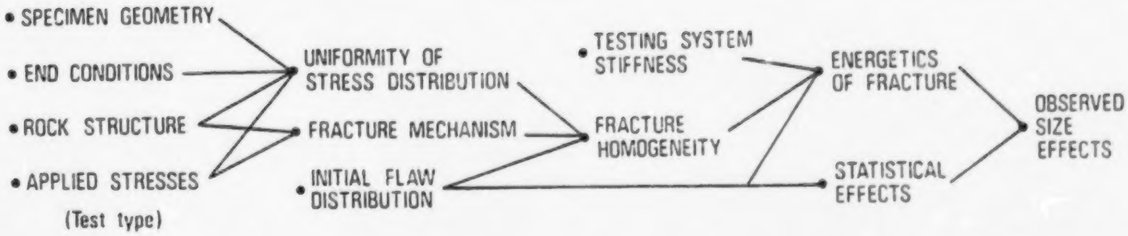
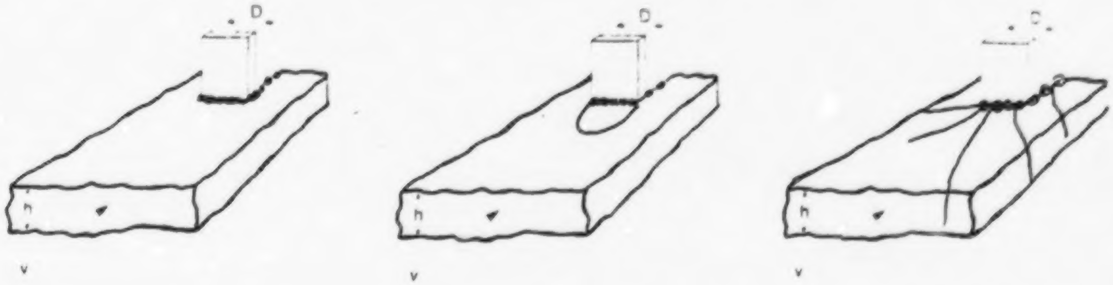

• SPECIMEN GEOMETRY
• END CONDITIONS
• ROCK STRUCTURE
• APPLIED STRESSES
(Test type)
UNIFORMITY OF STRESS DISTRIBUTION
FRACTURE MECHANISM
INITIAL FLAW DISTRIBUTION
TESTING SYSTEM STIFFNESS
FRACTURE HOMOGENEITY
ENERGETICS OF FRACTURE
STATISTICAL EFFECTS
OBSERVED SIZE EFFECTS

Figure 13 : General relationship between causitive factors and observed size effect (Brown and Gonano, 1975).

5.0 FAILURE MODES IN ICE

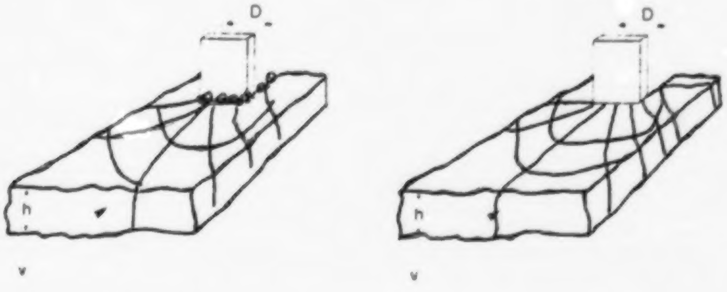
In the paper presented by Metge at this Workshop, a very good overview was given of the types of failure behaviour which have been observed in the field around Arctic structures. At a smaller scale in the laboratory, similar types of failure behaviour have been observed. In a recent study by Timco (1986) studying indentation processes in freshwater ice, five failure modes were distinguished (see Figure 14). In observing the tests it was apparant that there were certain key parameters that would dictate which failure mode predominated. Using the general scheme put forward by Palmer et al (1982), the failure modes were plotted in terms of the speed to diameter ratio and the structure width to ice thickness ratio. This produced a "failure mode map" which gave a very good indication of the conditions which were necessary for certain types of ice failure. This experimentally determinerd failure map is shown in Figure 15 along with the theoretically predicted map (from Palmer et al 1982) for comparison . There is good consistency of the results. The theoretical analysis and laboratory tests of this type give an indication of the parameters which influence the failure behaviour of ice. A major challenge facing ice researchers is the development of a similar failure mode map for full scale conditions.



CRUSHING (c)

CRUSHING WITH SPALLING (s)

CRUSHING WITH RADIAL CRACKING (r)



CRUSHING WITH RADIAL AND CIRCUMFERENTIAL CRACKING (m)

RADIAL AND CIRCUMFERENTIAL CRACKING WITH BUCKLING (b)

Figure 14 : The failure modes observed in laboratory tests of indentation in freshwater ice (Timco, 1986).

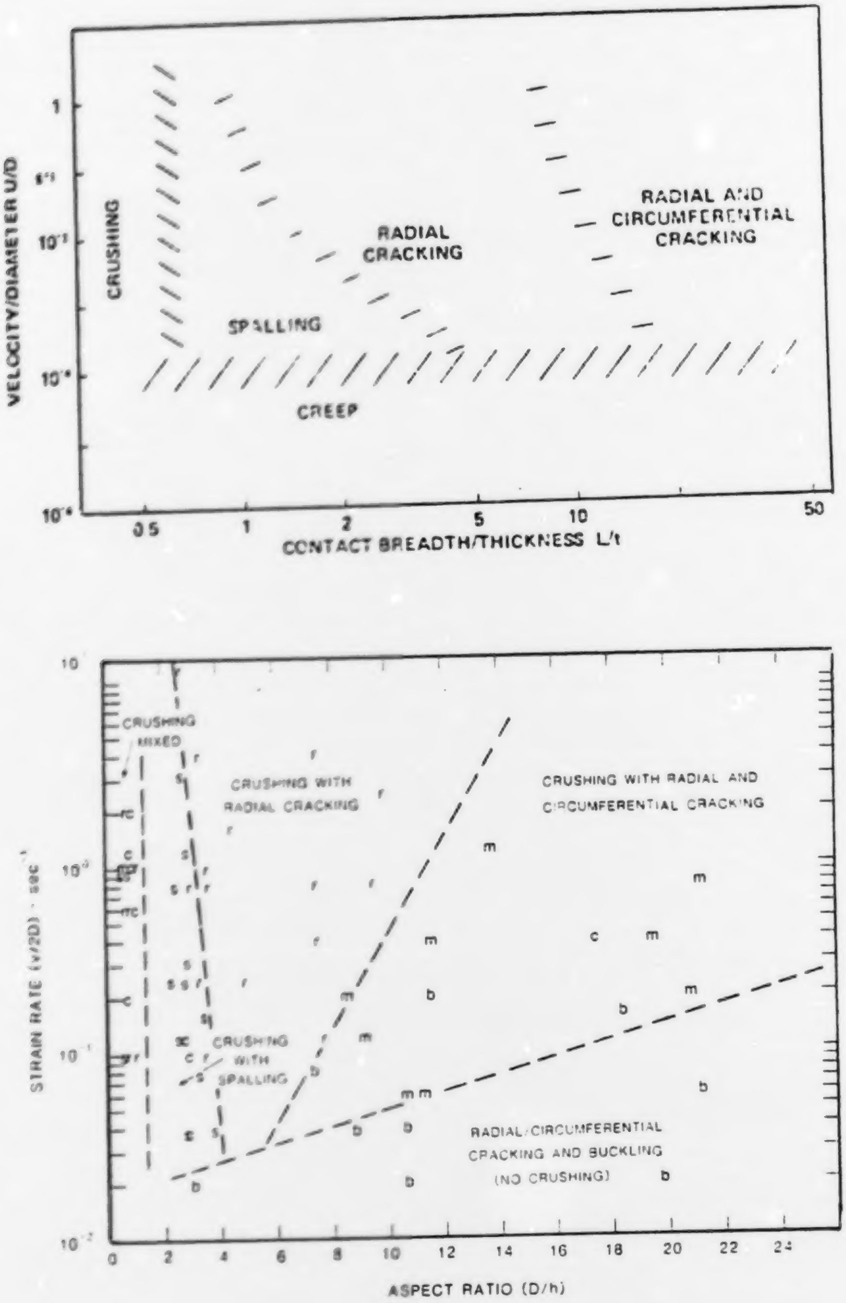


Figure 15 : **Comparison of theoretical predicted (Palmer et al, 1982) and experimentally measured failure mode maps in ice (Timco, 1986).**

6.0 SOME UNANSWERED QUESTIONS

1. IS THERE REALLY A SCALE EFFECT
    - IN STRENGTH?
    - IN ICE LOADS?

2. WHAT IS THE CORRECT VALUE OF ICE "STRENGTH" ON A LARGE SCALE? HOW IS IT RELATED TO THE "STRENGTH" THAT WE MEASURE IN THE LABORATORY?

3. ON THE MICROSCOPIC LEVEL, DOES THE ICE FAIL IN THE SAME WAY IN SMALL SCALE/LARGE SCALE SITUATIONS?

4. HOW DO PARAMETERS SUCH AS SYSTEM STIFFNESS, SAMPLE PREPARATION, ETC. AFFECT THE MEASURED ICE STRENGTH, ESPECIALLY AS THE SCALE GETS LARGER?

5. IN LABORATORY TESTING OF ICE/STRUCTURE INTERACTIONS, WE MEASURE A LOAD AND CALCULATE A PRESSURE. IN THE FIELD, WE MEASURE A PRESSURE AND INFER THE LOAD. HOW ACCURATE IS THIS?

6. DO WE SEE THE SAME MACROSCOPIC FAILURE MODES IN ICE IN THE FIELD AS IN LABORATORY TESTING?
   IS THE FAILURE MODE "MAP" THE SAME?

7. CAN WE PREDICT THE FAILURE MODE IN A FIELD SITUATION IF WE KNOW THE ICE SPEED, STRUCTURE WIDTH AND ICE THICKNESS?
   WHAT ELSE MUST WE KNOW?

8. WHAT ABOUT LARGE FLAWS IN SEA ICE SHEETS?
   ARE THE NUMBERS/DENSITIES OF FLAWS PREDICTED BY THE LAB TESTS REASONABLE?

9. WHAT ABOUT TIME? WE KNOW THAT TIME IS A VERY IMPORTANT ELEMENT IN THE FAILURE LOAD AND PROCESSES IN ICE. HOW DO WE CORRELATE "TIME" IN LABORATORY TESTS WITH THOSE IN THE FIELD SITUATION?
   WHAT IS THE EFFECTIVE "STRAIN RATE"?

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Session 6 - Discussion

The following questions, answers and comments formed part of the discussion period in Session 6.

I. Bayly:

It seemed to me that lab type specimens are fully loaded across the section, whereas the St. John and Daley data come from USCGC POLAR SEA data measured on a full panel during ice breaking, where contacts were quite irregular.

G. Timco:

That's true. In a laboratory we can control and measure precisely the area of contact of the ice specimen. In icebreaking trials this is not possible and the interpretation of these tests are more subjective. It is necessary to be familiar with the limitations of this type of data before applying it to a design situation.

* * *

R. Weiss:

From a design point of view one question is whether one can depend on the existance of size effect, or, will one sooner or later encounter a relatively flaw free piece of ice? Presumably, dynamic events on Molikpaq have already established that one cannot always depend upon nonsimultaneous failure to limit ice loads.

G. Timco:

That, of course, is the critical question. Until we understand the reason(s) for the apparent size effect we must be cautious in its use in designing offshore structures.

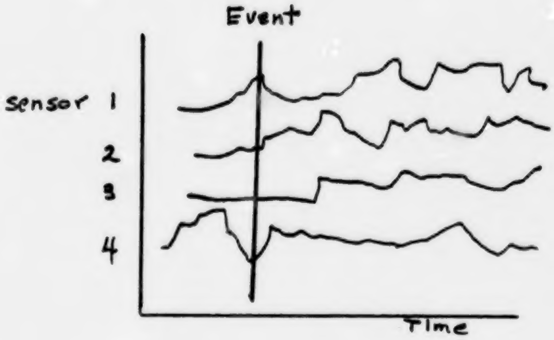
I. Jordaan:

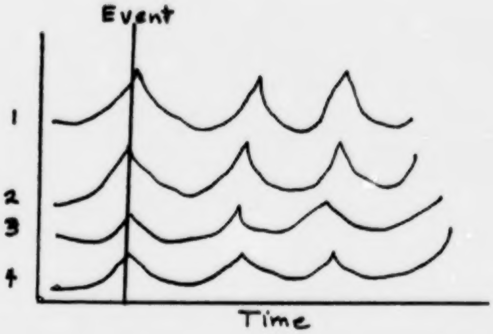
This is true, although the average pressures at maximum load, even during "phase-lock", were (as far as I can deduce) significantly less than small scale indentation pressures. The best way to treat flaws from an analytical point of view is to use probability theory. Then the probability of a flaw-free piece of ice can be included in the analysis

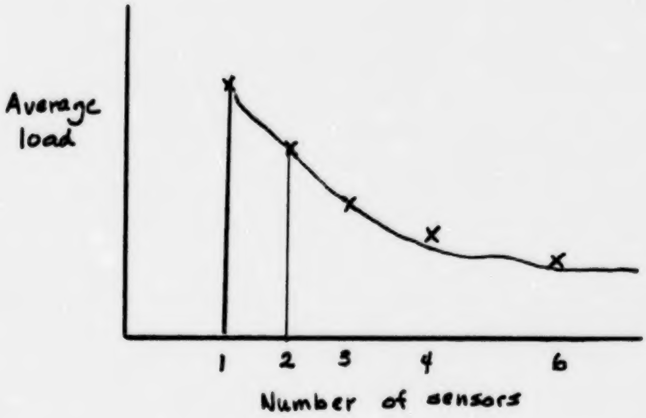
* * *

R. Pilkington:

With the Molikpaq data we compared (Wright, Pilkington, et al. IAHR, 1986) the average load (or average pressure) over 1, 2, 3 to 6(?) sensors each about 1.2m wide. We found a definite reduction in average load (pressure) between 1.2 and about 7.2m widths due to non-simultaneous failure processes. With dynamic pulsations, failure is simultaneous and no reduction in average load would be expected.







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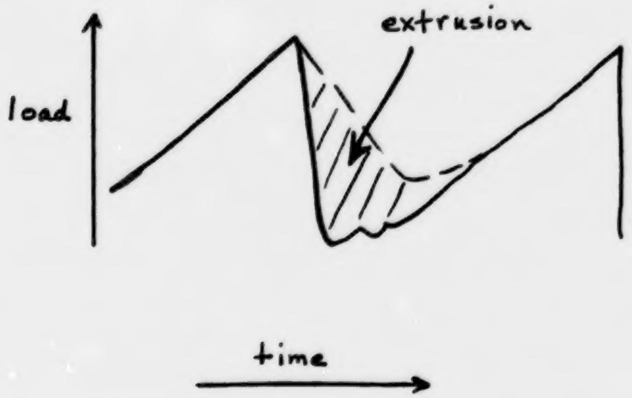
R. Pilkington:

You show the ice extrusion occuring after the load has dropped off. Would you expect the extrusion process to start immediately after failure (pulverisation) occurs and diminish with time?



I. Jordaan:

Extrusion would start with the pulverisation event, but the reduction in load usually happens quite rapidly, so that there would be little time for extrusion during the event. As the extruding layer gets narrower, the material becomes harder to move so that the load increases. The rate of extrusion (expressed in terms of volume) would be approximately constant if the ice is moving at a constant rate. This would be modified by elastic movements of ice and the structure if these are significant.

* * *

M. Metge:

- Flaws:
    - definitions of flaws - thinning

      - crack
    - flaws originating from failure zone

1. Regarding the issue of existing flaws in ice, I suggest that there might be two different kinds of flaws:

- one due to things such as melt ponds and old ridges. These flaws affect the geometry of the interaction but do not act as "cracks" which might propagate.

- the second kind consists of existing cracks and microscopic flaws in the crystal structure. These would be important in fracture mechanics considerations.

2. Regarding cracks, I suggest that the cracks caused by the previous moments of ice failure may be more important in fracture mechanics considerations of an ice indentation process than the pre-existing cracks in the ice, many of which have had ample opportunity to "heal" due to repeated melting and re-freezing (in the case of multi-year ice).

I. Jordaan:

1. I agree entirely with this suggestion. Flaws initiating flexural failure could be combined with the analysis by Hallam et al. quoted in my paper.

2. Stress concentrations play an important role in causing new cracks, as suggested by Lorne Gold. Nevertheless, temperature fluctuations and flexing of ice sheets will cause cracks to form continually (these are two examples only of possible mechanisms). The relative role of new and pre-existing cracks is, in my opinion, an open question.

* * *

J. Lever:

Dynamic effects in ice were explained with crushing relaxation and viscous extrusion. Does this always happen and what triggers synchronization?

I. Jordaan:

Often, other modes of failure such as spalling (flaking) and flexure (buckling) take place. The precise reasons for the shift from one mode to another are not well established. Presumably all fracture events will have a cyclic nature (breaking and subsequent clearing).

A possible explanation of synchronization is that the energy transferred from the structure to the ice causes the pulverisation zone to enlarge; this enlargement in turn would increase the load fluctuation, and energy variations would consequently increase, and so on. It is important to analyse data statistically to see whether synchronisation is possibly a random superimposition of effects. This provides an alternative possible explanation.

* * *

L. Gold:

You stated that the Sanderson Effective Pressure-Area curve could be misleading. Would you please enlarge on what you mean.

G. Timco:

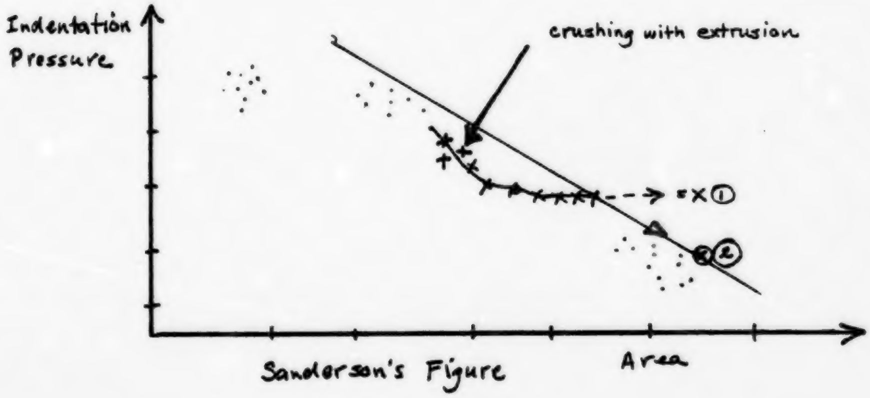
The curves could be misleading for a number of reasons. First, the data plotted on the graph contains information from a variety of ice types and test configurations. We've seen that there is no strong evidence to indicate a size effect for any one type of test configuration (or failure mode of ice) and so using Sanderson's curve to extrapolate within a data set may be in error. Also, the data should be regarded as an apparent (or calculated pressure) averaged over the whole structure. There is no reason to believe that the local pressures on a wide structure are as low as those indicated on Sanderson's curves.

* * *

M. Metge:

Misleading nature of Tim's curve

Sanderson's curve of indentation ice pressure versus area is not "misleading" in itself but there is a danger that it might be misinterpreted in a misleading fashion. One confusion might come from the definition of "indentation", which may include such failure models as pure crushing, or crushing with flaking or crushing with extrusions. Each of these different failure modes may follow an individual, and different curve of pressure versus area as shown in the figure.



As long as we are not extrapolating beyond the existing data there is no problem but if we want to extrapolate, we must extrapolate using the curve for each specific failure mode rather than the line which bounds all the data sets. The difference may be a factor of two or three.

* * *

R. Pilkington:

You showed the stress distribution for a spherical indentor pushing into an ice sheet which showed peak stresses at the edges of the indentor. What sort of stress distribution would you expect for the Molikpaq - semi-infinite in the horizontal plane and an "indentor" much wider than the ice in the vertical plane?

L. Gold:

The stress distribution in the ice in front of a structure such as the Molikpaq, will depend on the nature of the contact between the ice and the structure, the effective width of the structure and the speed at which the ice is moving relative to the structure. If the rate of movement of the ice is sufficiently high that its response is truly elastic, and if the ice is failing by continuous crushing, one would expect periodic episodes of stress concentration at the upper and lower surfaces of the ice cover, and at changes in direction of the surface of the structure, e.g., at corners.

* * *

Lorne Gold:

I want to support the comments made by Dr. Jordaan concerning the possible nature of the failure process during indentation. Under certain conditions of loading, a stress concentration can be expected to occur in the ice in the vicinity of the edges of a structure. It would be expected that failure would be initiated at the sites of stress concentration and that is would then progress inward from these sites. The failure process would be progressive, but occurring over a very short interval of time.

I. Jordaan:

I would like to thank Lorne Gold for his comments. Although stress concentrations would, as suggested, tend to initiate failure, the crushing mode could be initiated under uniaxial stress states without any special concentration.

Perhaps the stress concentrations are related to spalling failures, involving tensile stress; we agree on the main point, i.e. progressive failure over a short period of time.

SUMMARY

SESSION 7

SUMMARY SESSION

Jean-Paul Nadreau

The objective of this session was to allow the participants to draw conclusions from the sessions and to present recommendations which could be directed to appropriate organizations.

Session 1: Ice-structure Interaction in the Field.

During this session the nature of the ice-structure and ice-ship interaction in the field was described. Failure modes were identified and tentatively classified. Scarcity of large scale data was acknowledged.

The idea of recording the size of the ice blocks produced during a given event appeared interesting. In order to help classification, however, the implementation of it did not seem obvious; to be useful and representative, a minimum of measurements would be needed to lead to an acceptable evaluation of characteristic values such as mean and maximum.

A consensus was reached on the need for a consistent terminology describing the various forms of ice-structure interactions; the term "crushing" is actually too vague and comprises too many different situations. A manual describing, along with photographs, the numerous patterns encountered in ice-structure interactions would be a valuable asset. It was agreed to convey this need to the Snow and Ice Subcommittee of the Associate Committee on Geotechnical Research of NRCC.

Session 2: Design Requirements.

The presentations raised eventually the question of the sensitivity of the various models currently used to design offshore structures. With probabilistic approaches being used, a wide variety of "critical ice features" can generate the same global loads. The maximum value of the global load is critical but one knows that its distribution in space remains important and can produce significantly different stresses. Field observations and physical model testing should concentrate on the distribution of ice pressures across the structure.

Several comments were related to the question of pulsating loads and dynamic behaviour of ice and structures. Experience on the Molikpaq shows that pulsating loads are rather infrequent and that they occur when some very specific conditions are met. Among the conditions experienced during the 1985-86 season, one can identify ice velocity of about 0.1 knot, and a continuous ice cover that is laterally confined and generally thick. The grounded rubble formation which occurred in the 1987-88 deployment season appeared to suppress entirely pulsating loads.

Finally, ice interaction with spray ice islands has been identified as an interesting subject for study and more effort should be devoted to it.

Session 3: Review of Physical Properties of Ice.

Characteristics of features such as ridges and multiyear floes were presented. The amount of data is impressive but the session showed that more work is still needed for a complete coverage of the subject. Physical descriptions of ridges and icebergs are rather well known but size and shape distributions are not as readily available. The needs are essentially related to statistical characteristics of ice features such as the concentration, size distribution and velocities of multiyear floes.

During this session, the emphasis was put on the lack of data related to icebergs. There is an urgent need for more data which could lead to a better evaluation of parameters such as fluxes, arrival rates and scour distribution. An improved knowledge of these characteristics should lead to more realistic design models.

Session 4: Review of Mechanical Properties of Ice

This session confirmed that research on the mechanical properties of ice is an important activity. The various presentations showed that ice behaviour is dependent upon a large number of variables, and it is critical to identify clearly the most important ones. It was noted that it is through a constant dialogue between design engineers and scientists that a consensus on design properties can be reached.

Because of the various failure modes in ice, the failure behaviour is complex such that there is no universal conceptual model to link ice properties and design values. We do not understand the failure processes in ice and this precludes common agreement on what to measure. There is still a need for an agreement between researchers on testing methods; how should measurements be made, analyzed and reported.

Session 5: Testing Methods.

Directly related to the previous session, several projects designed to better characterize the ice were presented. These programmes were conceived to study the mechanical properties of ice through experiments such as friction, indentation and impact.

One of the projects presented was the medium and large scale indentation tests performed on iceberg ice in Pond Inlet, N.W.T. The discussion focused essentially on the sensitivity and cost vs benefit analysis which should be made before any test is envisaged. This is becoming extremely important when dealing with large scale tests. The questions to be asked are: how much is the cost per data point and how much influence will variation of the value of the property to be measured have on the final cost of the structure to be built? Also, how much evidence (i.e. how many data points) is needed before a design engineer will change his design values?

Another topic of concern was the dynamic behaviour of ice. Measurement of dynamic effects require appropriate equipment and fast recording. Proper analysis should be made to evaluate the contribution of the test rig to the dynamic behaviour.

Session 6: Scale Effects (physical and analytical)

Depending on the way data are presented, scale effect is more or less visible. The effect is widely acknowledged but reasons and physical explanations are not yet completely identified. When studies of full scale ice-structure interaction are made, emphasis should be put on the documentation of failure mechanisms and of the development of pulverized ice zones. This should help in complementing the failure mode maps already available for small scale experiments.

Due to the extensive cost of large scale experiments, available data are still limited. All new initiatives are welcome. it is clear that such projects should be joint ventures between government and industry. It was suggested also that logistical support should be obtained for the use of Hans Island as a permanent base for large scale ice-structure interaction studies.

ATTENDEES
Workshop on Ice Properties
June 21 & 22, 1988

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